A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-1
FM RECEIVERS

What Is Frequency Modulation?

MOTOROLA TRAINING INSTITUTE

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What Is Frequency Modulation?

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
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APPROVED BY THE STATE OF ILLINOIS
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PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

WHAT IS FREQUENCY MODULATION?

LESSON RA-1

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NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

As early as 1927, police started using radio to improve their efficiency by "breaking in" on local broadcasts. The police have since grown to be the largest single user of two-way mobile radio. Faster response to trouble calls, better use of available manpower and savings in tax dollars are the major reasons for this extensive use of radio communications.

WHAT IS FREQUENCY MODULATION?

Introduction

Today, almost all mobile two-way radio equipment uses frequency modulation rather than amplitude modulation. Therefore, if we are to think intelligently about the operation of present-day two-way communications equipment, we must thoroughly understand what is meant by frequency modulation--abbreviated FM.

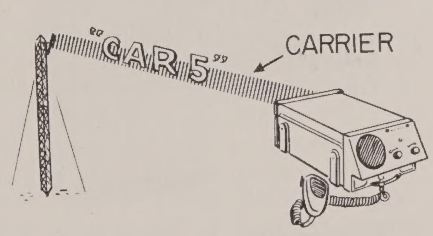
The FM receiver is remarkably free from noise and adjacent station interference. Also, the FM transmitter is more efficient in that it requires less power input for a given coverage than those used for AM (amplitude modulation). In this lesson, we will become familiar with FM and learn more about its marked advantages over AM.

FM is not particularly new. Not many years have passed, however, since it was first put to practical use. Back in 1939, the first successful state-wide mobile FM system was designed for the Connecticut State Police, by Daniel E. Noble, now Executive Vice President of Motorola Inc. Since then, FM has been accepted universally as the best modulation method for mobile two-way communications systems. World War II emphasized the growing need for reliable, noise-free communication in mobile applications; FM was the solution.

Today's widespread use of FM demands that you, the technician, think in terms of FM as readily as you do in AM. One of the best ways to approach FM is to compare it with AM. Let us start, then, with a quick review of AM and see how the two differ.

Amplitude Modulation

In any basic radio communications system consisting of a transmitter and a receiver, the transmitter produces and radiates a signal in the nature of high-frequency electromagnetic energy. The receiver must select the desired signal and reproduce the message in its original form. Because low-frequency (audio) energy cannot be radiated efficiently, a high-frequency wave, called the "RF" (radio frequency), is used to carry the message to the receiver. That is, the audio message is combined with this RF

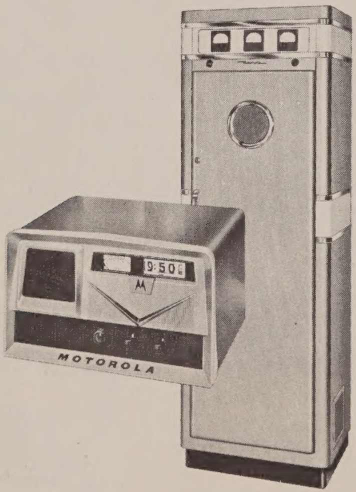


The Carrier in the Two-Way Radio System "Carries" the Message to the Receiver.

carrier, and in this manner the message reaches the receiver as part of the radiated signal. This process of combining the audio with the carrier is called "modulation".

In modulating the carrier at the transmitter it is possible to alter either the frequency or the amplitude.* If the audio causes amplitude changes in the transmitted RF, the system is known as "amplitude modulation".[1] If the audio signal causes corresponding frequency changes in the transmitted RF, the process is called "frequency modulation".

The function of the receiver, whether AM or FM, is to recover the original audio message



A Remote Control Console and Base Station Used for Two-Way Communications.

from the carrier and reproduce it in the speaker.

The AM Transmitter

Figure 1A is a block diagram of a simple AM transmitter. The RF carrier, generated in the oscillator stage, is constant in both amplitude and frequency. This RF carrier (represented by the closely spaced waves) is amplified in the power amplifier, fed to the antenna, and then radiated into space. Something has happened, however, to the steady RF amplitude in the power amplifier, as you can see by the output waveform. In the power amplifier stage, modulation has taken place. An audio voltage, applied to the power amplifier at the same time as the RF, has changed (modulated) the RF amplitude according to the amplitude of the audio signal. Let's see how this happened.

When sound waves strike the microphone diaphragm they are changed into corresponding audio voltages. These low-frequency mike voltages are constantly changing both in amplitude and in frequency. This audio voltage is then applied to an audio amplifier (or modulator) where it is amplified to the level required to properly modulate the PA (power amplifier). Thus, there are two voltages applied at the same time to the PA. One of them is the steady RF from the oscillator; the other is the audio (modu-

* "Phase" modulation is also possible; it is considered as a form of frequency modulation and will be discussed later in the training.

[1] See TM 11-668 FM Transmitters and Receivers, pages 2-4; also FM Transmission and Reception, by Rider and Uslan, pages 1-10.

lating) signal from the audio amplifier. Although the PA operates as an RF amplifier, its output is made to vary according to the amplitude of the audio signal. The audio signal is a low-frequency alternating voltage. The positive half-cycle of the audio signal increases the RF output; the negative half-cycle lowers the RF output. This means the amplitude of the RF changes in exact accordance with the audio signal, while the frequency of the RF carrier remains constant. Hence the general statement: In amplitude modulation the frequency of the carrier remains unchanged, but the RF amplitude varies with the spoken message.

AMPLITUDE MODULATION

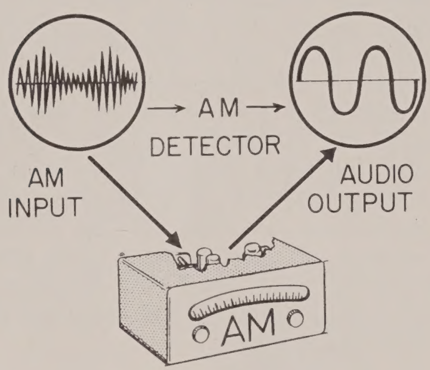
At the AM Transmitter, the Modulating Signal Produces Changes in the RF Amplitude.

Compared to the AM system, the FM system makes more efficient use of the power taken from the primary power source -- the car battery and generator in mobile equipment. The power output of the AM transmitter increases under modulation, to the extent that the power level at the peaks may be four times the power of the unmodulated wave. This means the level of the unmodulated carrier must be lower than the maximum power capabilities of the final output tube. Also, because of the high current and voltage peaks, the power supply and transmitter are bulky, heavy and costly. By comparison, the FM transmitter operates at full power output at all times; its output does not increase during modulation. This greater RF power level means increased coverage for the same amount of power taken from the source. Also, the FM transmitter is smaller, lighter and more economical to build.

The AM Receiver

The desired RF carrier reaches the antenna of the AM receiver, figure 1B, together with RF carriers from other transmitters. The first action within the receiver is the selection of the desired carrier from all the rest. Because this RF voltage at the antenna is very weak, it must be amplified. Figure 1B shows only one block for the RF amplifier, but in the communications receiver there may be more than one high-gain stage. From the RF amplifier this signal is applied to the detector, a device that reacts to amplitude changes. Since the amplitude of the RF waveform is

changing according to the spoken message at the transmitter, the detector output is an audio voltage corresponding to the audio waveform produced at the transmitter microphone. This signal is then applied to an audio stage, which amplifies it sufficiently to reproduce the message in the speaker.



Incoming Amplitude Variations Produce an Output at the AM Detector.

In connection with the detector's response to amplitude variations, we should also talk briefly about noise voltages in the receiver itself. Almost all these noise voltages are amplitude variations. Therefore, noise voltages reaching the AM detector will be heard in the speaker. These noise voltages may be (1) man-made, (2) natural noises from atmospheric disturbances, or (3) they may be generated in the receiver itself. (We will study more about noise in a later lesson.)

The Frequency Modulation Transmitter

Figure 2 shows the arrangement of a very simple type of FM transmitter. The oscillator serves the same purpose in the FM transmitter as it does in the AM system -- to generate an RF voltage of constant amplitude and frequency. There is a big difference, however, when an audio voltage is introduced. In an AM system, the audio produces amplitude variations in the carrier; in an FM system, the audio produces frequency variations. Let's see how this happens. Figure 2 shows a simple Hartley oscillator, with its frequency determined almost entirely by the inductance and capacitance of the tank circuit, L and C. A "condenser microphone" is connected in parallel with the tank so that it becomes a part of the total capacitance of the tuned circuit.

This type of microphone is constructed of two metal plates, slightly separated from each other, forming a small capacitance. One plate is fixed, the other is movable. The movable plate is the mike diaphragm. When it is moved back and forth by the sound waves, the spacing between the two plates varies, and the capacitance of the microphone changes. This varying capacitance in parallel with the tuned circuit alters the total capacitance, changing the oscillator frequency.

As the microphone diaphragm moves closer to the stationary plate, the capacitance increases and the frequency decreases. When the diaphragm moves away from the other plate, the capacitance decreases and the frequency increases. Thus, as the diaphragm continues to move back and forth with the sound waves, an FM signal is produced.

FREQUENCY MODULATION

At the FM Transmitter the Modulating Signal Produces Changes in the RF Frequency

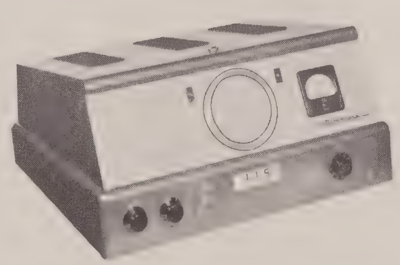
Figure 2 shows the waveform of this FM signal in the oscillator plate circuit. The carrier frequency varies with the audio, but the amplitude remains constant. At certain points the waves are close together, representing a relatively high frequency. At other points the waves are further apart, representing a lower frequency. The plate circuit is tuned to the unmodulated oscillator frequency. The FM signal is coupled from the plate circuit to the transmitting antenna.

Very little audio power is required in the FM transmitter illustrated in figure 2. This is another important characteristic of frequency modulation. Regardless of the total RF power output, only a small amount of audio modulating power is needed in an FM transmitter.

Extent of Frequency Change

While discussing frequency variations of the RF carrier, nothing has been said so far as to what extent the RF signal varies above and below the carrier frequency, nor has anything been said as to how often or at what rate the frequency changes. These factors are important and we must know how they are controlled by the audio signal.

Figure 3A shows a typical FM waveform which represents the output of the FM transmitter of figure 2. From the beginning of



A Typical "Desk Top" Base Station Used for Two-Way Communications.

the waveform to "point 1", the FM frequency is constant. This is an unmodulated RF wave. Then it is modulated between points 1 and 2, the RF increasing in frequency and the waves crowding together. (At 2 the RF reaches its highest frequency.) Between 2 and 3, it is returning to its average or unmodulated frequency. From point 3 to point 4, the carrier swings below its average frequency, the lowest value occurring at point 4. At point 5 the RF has again returned to its normal unmodulated value, ending a complete FM cycle.

Now that we have seen the nature of the frequency modulated wave of figure 3A, let's inspect the audio voltage (figure 3B) which causes this modulation pattern. The audio voltage sinewave is shown in figure 3B. Up to point 1 on the figure the audio voltage has zero amplitude, and the corresponding RF voltage, directly

A Strong Audio Modulating Signal Causes Large Frequency Changes in the Carrier.

above, is unmodulated. Between 1 and 3 the audio goes through a positive alternation; during this same period, the RF frequency (Fig. 3A) increases and returns to normal. At point 2, where the audio is maximum positive, the RF has its greatest frequency increase. Between points 3 and 5 the audio changes polarity, so that it is now negative. The RF frequency between points 3 and 5 again varies but in the opposite "direction", that is, it swings below its average frequency. At point 4 the audio voltage is maximum negative, and this is where the maximum "below average" RF change occurs. From figures 3A and 3B we see that every time the audio goes positive, the RF frequency increases; every time the audio is negative, the frequency decreases.

We can also let figure 3B represent the change in capacitance of the condenser microphone. The center line of the waveform will then represent the average capacitance of the microphone. When the waveform is above or below center, it will represent the mike diaphragm moving closer to or further away from the fixed plate and causing the RF frequency to increase and decrease. The next question to consider is the effect of applying a stronger audio signal--talking louder into the mike. This is illustrated by comparing figure 4A with 3A, and 4B with 3B.

Let's assume some definite values of frequency changes in the

A "Weak" Audio Modulating Signal Causes Small Frequency Changes in the Carrier.

RF waveforms of figures 3A and 4A. Suppose that in 3A the RF frequency increases 500 cycles above and decreases 500 cycles below the unmodulated frequency. At point 2 the RF is 500 cycles higher and at point 4 it is 500 cycles lower than the unmodulated frequency. Now let's look at the audio waveforms of figure 3B and 4B. Compared to figure 3B, the audio at 4B has twice the amplitude. In a well-designed system the RF will vary twice as much from average. That is, at 2 and 4 of figure 4A, the frequency should be 1000 cycles above and below the average RF value. From this discussion of figures 3 and 4 we learn that the amount of frequency change in the RF is controlled by the amplitude of the audio voltage. A weak audio input does not cause as much frequency shift as a strong one.

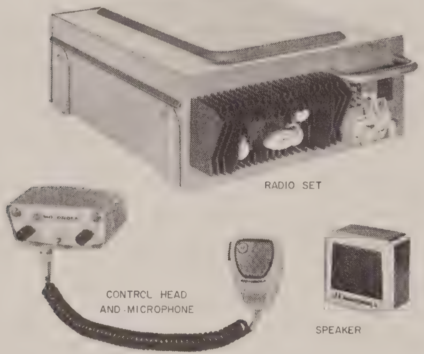
We can make a further analysis of this action by considering the change of capacitance caused in the condenser mike of figure 2. If we talk louder, the diaphragm of the mike vibrates more vigorously, causing a greater variation in mike capacitance. This, in turn, produces a greater change in the oscillator frequency.[2]

Rate of Frequency Change

Now that we know what determines the amount of carrier frequency shift, the next problem to consider is the rate at which these frequency changes occur -- stated as the number of changes per second. We can determine the answer from figures 5 and 6. Figure 5B shows an audio voltage producing frequency variations in the RF waveform of 5A. Assume the frequency of this audio wave is 1000 cps (cycles per second). Every time the audio goes positive, the RF increases in frequency; and every time the audio goes negative, the frequency decreases. If the audio has 1000 complete changes per second, the RF will change frequency, above and below average, 1000 times. From this we learn that the audio frequency controls the rate of change of the RF.

Let's see if this holds true in figure 6. The audio of 6B has twice as many cycles occurring in a given amount of time as that of 5B so it must have twice the frequency, or 2000 cps. Each time the audio of 6B changes positive and negative, the frequency increases and decreases. The audio

[2] See TM 11-688 FM Transmitters and Receivers, pages 15-17; also FM Transmission and Reception, by Rider and Uslan, pages 29-32.



A "Trunk Mount" Type of Mobile Two-Way Radio. The Speaker, Control Head and Microphone are Located Near the Driver.

having 2000 complete changes in one second causes the RF to change its frequency 2000 times per second. Therefore, in an FM system, the audio frequency controls the rate of change of the carrier frequency.[3]

Deviation

Thus far in talking about FM and frequency changes we have avoided a few terms commonly used by engineers and technicians. One often used term is "center frequency". This is the mid-frequency of the FM wave and corresponds to the unmodulated carrier. In figure 3A, from the beginning of the wave up to point 1, the RF is at its unmodulated frequency, and this is center frequency. At points 3 and 5, the RF is again momentarily at center frequency.

"Deviation" is another frequently used term. This refers to the amount of frequency change above and below center frequency. In analyzing the frequency changes taking place in figures 3 and 4 we gave examples of deviation. For figure 3A we assumed changes of 500 cycles above and below center frequency. The deviation is then 500 cycles. We usually write this "$\pm$500 cycles", and say, "a deviation of plus and minus 500 cycles". In practice the deviation of the average FM transmission is greater than 500 cycles and is expressed in terms of kilocycles--we might expect to see "$\pm$15 kc.". Note that the "deviation bandwidth" for a $\pm$15 kc deviation is 30 kc; this is the total frequency swing.

Quick Review
What have we learned?

1. In an FM transmitter, audio modulation causes the frequency, but not the amplitude, of the RF to change.

2. This change of carrier frequency above and below center frequency is known as deviation.

3. The amount of deviation is controlled by the strength (or amplitude) of the audio signal.

4. The rate of change or number of deviations per second is determined by the audio frequency.

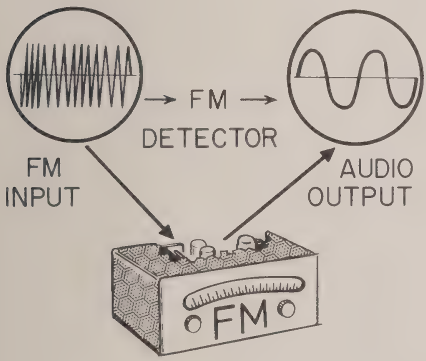
[3] See TM 11-668 FM Transmitters and Receivers, pages 15-17; and FM Transmission and Reception, by Rider and Uslan, pages 27-32.

5. Deviation is expressed as "± ...kc".

6. Deviation bandwidth is the total swing, and is twice the stated deviation.

The FM Receiver

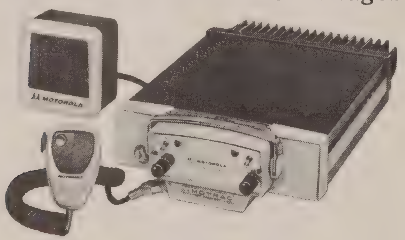
We have seen how an FM signal is generated and we know that the audio message is contained in the carrier deviations. In order to complete our system using frequency modulation, we now require a receiver which will recover the audio signal from the FM wave. The fundamental difference is in the type of detector. The AM receiver has a detector which responds to amplitude changes; the detector in the FM receiver must be sensitive to frequency changes.



Incoming Frequency Variations Produce an Output at the FM Detector.

Figure 7 is a partial block diagram and simplified circuit of an FM receiver. The incoming signal is an FM carrier and it is transferred from the antenna to the RF amplifiers. The operation of the RF amplifier stage in an FM receiver is the same as in the AM receiver. From the RF section, the amplified signal is coupled to the FM detector by means of a transformer which has a tuned primary and two tuned secondaries. The primary is tuned to the center frequency, but the secondaries are tuned to frequencies above and below center, respectively. Assuming a center frequency of 455 kc, secondary S1 may be tuned to 475 kc, which is 20 kc above center, in which case secondary S2 will be tuned to 435 kc, which is 20 kc below center. A load resistor (R1) in series with a diode rectifier (D1) is connected to secondary S1. During the positive alternations of the applied RF voltage, diode D1 conducts current in the direction shown by the arrows. (In these lessons we will make use of the negative to positive direction of current in order to coincide with the direction of electron flow). This current produces a voltage across R1 which is approximately equal to the RF voltage in the S1 secondary. The RF filter capacitor across R1 maintains the resistor voltage at a steady DC value. Thus, an incoming signal produces a voltage across R1, having the polarity indicated in figure 7 and an amplitude determined by the applied voltage.

Secondary circuit S2 is identical to S1 and operates in the same manner, the RF of secondary S2 being rectified to a DC voltage across R2. The two secondary circuits, however, operate independently of each other---the only common connection is at the resistors. Insofar as the output is concerned, the voltage of R1 and R2 are in series with each other but have opposing polarities. The output voltage will then be the difference of these two voltages.



A Modern, Low-Drain Two-Way Radio Having a Completely Transistorized Receiver and Power Supply.

Figure 8 shows what happens when an FM signal is applied to the circuit. (For convenience, figure 8 shows only the load resistors, R1 and R2, of figure 7.) Figure 8A indicates that when the center frequency of 455 kc is present, the voltages of R1 and R2 are equal in value. This is true because the secondaries are off resonance by the same amount and the resulting voltages in the secondaries are equal. (We have assumed 5 volts across each resistor for convenience.) The output terminals, A and B, are at the same charge or potential. Since voltage is the difference between two charges or potentials, the voltage across AB is zero. (A voltmeter connected across A and B of figure 8A will record zero voltage.) Thus, for the FM detector, zero output voltage occurs when the applied signal is at center frequency. The next step is to determine what happens when the signal varies above or below center frequency.

When the incoming signal swings above center (we call this positive deviation), the frequency is higher than 455 kc and the tuned circuit of S1 is nearer to being in resonance with the incoming signal. Being nearer to resonance, the RF voltage in the tuned circuit increases and the resulting voltage across R1 must also increase. At the same time, the tuned circuit of S2 is further from being in resonance and the RF voltage in S2 decreases. This results in less voltage across R2. In figure 8B we have assumed the voltage of R1 increases to 6 volts while that of R2 decreases to 4 volts. The difference between A and B is now 2 volts and A is positive with respect to B. Thus, when the incoming signal is above center frequency (positive deviation), the FM detector produces a positive output voltage.

When the incoming signal swings below center frequency (negative deviation), the condition of figure

A Compact, Low-Drain Two-Way Radio Which Makes Extensive Use of Transistors.

8C occurs. At a frequency below center, S2 is nearer to being resonant and produces a larger voltage, this time at R2. Secondary S1, on the other hand, is further from resonance and its output voltage decreases. As assumed in Figure 8C, the voltage across R2 increases to 6 volts while that across R1 decreases to 4 volts. Again there is a difference of 2 volts between terminals A and B, but A is now negative with respect to B.

To summarize, whenever the signal is at center frequency the output is zero. During a positive deviation of the signal the output becomes positive, but for negative deviations the output swings negative. Thus, the FM detector is a device that converts frequency variations into changes of voltage.

At the FM transmitter the audio amplitude determines the amount of deviation while the audio frequency determines the rate of deviation. At the receiver this process must be reversed. That is, the amount of deviation from center should determine the audio amplitude (amount of output voltage), while the rate of deviation should determine the audio frequency. Let's see how this happens!

The amount of output voltage of figure 7 depends upon the difference or the unbalance of voltages across R1 and R2 The resistor voltages depend upon the amount of RF voltage in the secondaries. The secondary voltages, in turn, are determined by how near the circuits are to being resonant with the incoming signals. For higher deviations the frequency is closer to resonance in one secondary and further from resonance in the other. This results in a greater difference in the resistor voltages and a higher voltage at the output terminals. Thus, the higher the deviation, the higher the output voltage; the lower the deviation, the lower the output voltage. This satisfies our first requirement-the amount of deviation determines the amount of output voltage (audio amplitude).

Our second requirement is that the rate of deviation determines the frequency of the output voltage. Every time the signal deviates from above center to below center, the output changes from positive to negative, and vice versa. The detector output thus changes polarity at the same rate that the frequency swings above and below center. Hence, the frequency of the recovered audio must coincide with the rate of deviation of the applied FM signal.

Lightning and Other Sources of "Noise" Interfere With AM Reception.

Other differences between the FM receiver and the AM receiver will be discussed in later assignments. For the purpose of this assignment, however, the basic difference is in the type of detector used. The circuit of figure 7 is not used in present day receivers, but it best illustrates FM detection. Communications type FM receivers usually incorporate a circuit known as a "discriminator" for FM detection. As we shall see later, the action is similar to that shown in figure 7.[4]

At the beginning of this lesson we said one purpose of the assignment was to determine what is meant by FM. In addition, we indicated certain inherent advantages of FM. These advantages will now be discussed.

FM is More Interference-Free

Almost all noise energy is characterized by its irregular amplitude variations. In the AM system the detector is designed to respond to amplitude variations. Little can be done at the detector to eliminate noise voltages without sacrificing the desired signal modulation. Although circuits have been devised which seemingly distinguish the sharp-peaked noise waveforms from the more even waveforms of a spoken message, these circuits, at best, leave a lot to be desired and are only partially effective. Other types of amplitude limiting of noise pulses are successful to some extent but under adverse conditions the results are poor.

FM receivers incorporate special circuits known as "limiters" which drastically reduce or eliminate amplitude variations. This does not affect the audio message,

[4] See FM Transmission and Reception, by Rider and Uslan, pages 249-251 and 293-298.

for in frequency modulation all of the intelligence is contained within the frequency deviations. Eliminating amplitude changes has no effect on frequency deviations. Thus the FM receiver, by means of limiter circuits, is free from almost all noise interference--this is probably the most outstanding advantage of FM.

Lightning and Other Noise Sources Have Little Effect Upon FM Reception.

FM signals are also less sensitive to interference from other signals. For an AM system, a desired signal must be at least 50 to 100 times stronger than an interfering signal in order to override the latter to the point where it causes no trouble. For an FM system, however, interference-free operation is often maintained with a ratio as low as 2 to 1.[5]

The FM Transmitter is Efficient

The FM transmitter is more efficient than the AM transmitter. If a power tube has a rating of 60 watts, the entire 60 watts can be utilized as carrier power in FM. The FM carrier, you will recall, does not increase in power during modulation. The FM transmitter may thus work at maximum output at all times. In an AM system using the same tube, 20 watts must be reserved for audio modulation, leaving only 40 watts remaining for RF power. The carrier power is then only 40 watts for the AM transmitter, but for FM it is 60 watts. Also, where battery power is at a premium (as it is in most mobile applications) the ability to use all the power available for the carrier means greater coverage. Furthermore, the additional power required to operate the higher power audio stages in the AM transmitter is not necessary in FM.

FM Bandwidth

Every system must have its drawbacks as well as its good points, and the bandwidth required for FM transmissions is a disadvantage at the present state of the art. Commercial FM transmissions (88-108 mc) have a deviation of plus and minus 75 kc, a deviation bandwidth of 150 kc. In addition, an unused " guard

[5] See TM 11-668 FM Transmitters and Receivers, pages 32 and 33; also FM Transmission and Reception, by Rider and Uslan, pages 44-46 and 210-212.

band'' is needed between channels. The total bandwidth for each commercial FM broadcast is then 200 kc. Even for voice communications in 2-way communications systems, where the deviation has been reduced to as low as ±5 kc, channel spacings must be slightly wider than theoretically needed for AM voice transmissions.

You have now completed your first assignment. If you have not studied the ''Introduction'' sent with this first lesson, do so at this time. In this booklet you will find specific directions for completing and sending in the examination at the back of this lesson.

IMPORTANT WORDS USED IN THIS LESSON

AM DETECTOR: A demodulator incorporated in an AM receiver which recovers the desired intelligence from the amplitude variations of the AM carrier.

AMPLITUDE MODULATION: A system of modulating the RF carrier, whereby the amplitude of the radiated signal is made to vary in accordance with the modulating voltage, but the carrier frequency remains constant.

CARRIER: RF energy of a specific frequency generated at the transmitter and radiated into space. The carrier, when modulated, serves to transport the intelligence to the receiver.

CENTER FREQUENCY: The term applied to the average carrier frequency of an FM wave. This center frequency is evident when the FM carrier is undisturbed (in the absence of modulation).

DEVIATION: Frequency changes of the FM carrier, resulting from modulation. Deviation is expressed as the extent of frequency change from the center frequency.

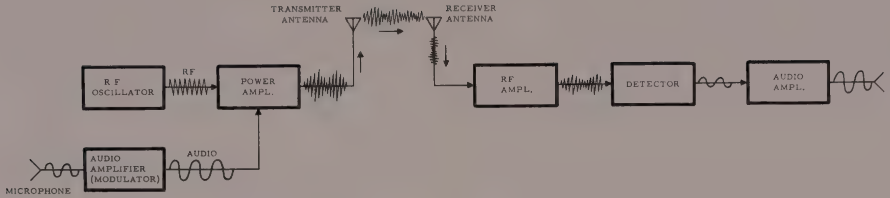
DEVIATION BANDWIDTH: The total frequency swing of the modulated FM wave. Numerically, deviation bandwidth is equal to twice the stated deviation.

ELECTROMAGNETIC WAVE: Radiant electric energy, such as that emitted from the transmitter antenna. Electromagnetic energy consists of an electric field and a magnetic field, both of which are essential for continued propagation of the wave. Light and heat are other examples of electromagnetic energy---the difference is in the wavelength (frequency).

FM DETECTOR (DISCRIMINATOR): A demodulator incorporated in an FM receiver, which recovers the desired intelligence from the deviations of the FM carrier. This is accomplished by converting the frequency variations into an audio voltage.

FREQUENCY MODULATION: A system of modulating the RF carrier, whereby the frequency of the carrier is made to vary in accordance with the modulating voltage, but the carrier amplitude remains constant.

STUDENT NOTES

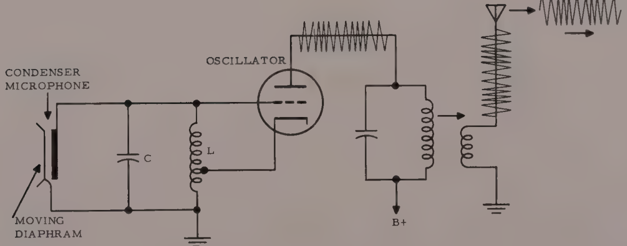


AMPLITUDE MODULATION TRANSMITTER

FIGURE 1A

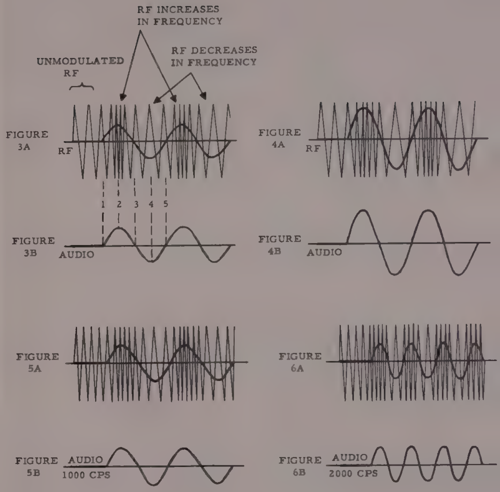
AMPLITUDE MODULATION RECEIVER

FIGURE 1B



FREQUENCY MODULATION TRANSMITTER

FIGURE 2



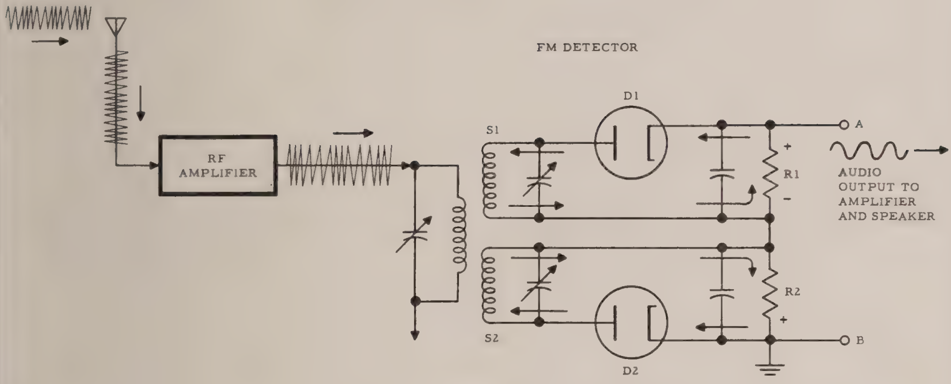
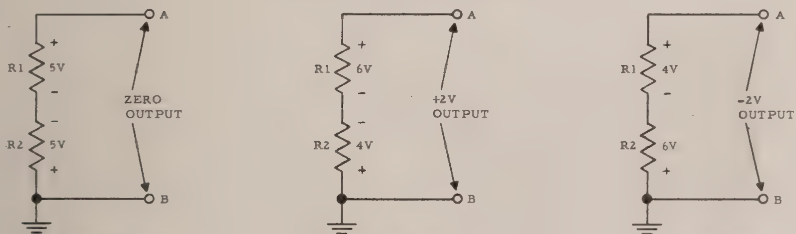


FIGURE 7

FM RECEIVER, SHOWING FM DETECTOR



ZERO DEVIATION
FIGURE 8A

"+" DEVIATION
FIGURE 8B

"–" DEVIATION
FIGURE 8C

FM DETECTOR- - OUTPUT VOLTAGE

Motorola Training Institute
4501 West Augusta Blvd., Chicago 51, Ill.

Please PRINT or use STAMP.

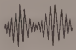
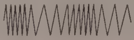
Name ______________________ Student No. ______

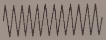
Street ______________ Zone ____ Date ______

City ______________ State _______ Grade ______

Examination, Lesson RA-1

1. In the blanks provided, write the letter corresponding to the correct waveform.

A.  B. 

C.  D. 

Audio Waveform ______
AM Waveform ______
FM Waveform ______
Unmodulated RF ______

2. The waveform below contains points of center frequency, positive deviation, and negative deviation. Indicate the correct corresponding letters in the spaces at the right.

A. B. C.

Negative Deviation ____
Positive Deviation ____
Unmodulated RF ____

3. UNDERSCORE the correct words in the following statements.
   The amount of audio voltage applied to the modulator in the FM transmitter determines the (amount)(rate) of deviation.
   The audio frequency determines the (amount)(rate) of deviation.

4. CHECK any and all correct answers.
   In an FM receiver, the discriminator:
   A. Produces an audio output voltage from the incoming FM deviations. ______
   B. Recovers the "message" from an FM signal. ______
   C. Maintains a constant DC voltage output even when the incoming signal swings higher or lower in frequency. ______
   D. Output becomes alternately positive and negative when an FM signal is applied. ______

5. In the space to the right of each of the following statements, write FM or AM, whichever applies.
   A. Modulation does not change the total power output of the transmitter. ______
   B. When modulated, the frequency of the transmitter output varies with the modulating signal. ______
   C. During modulation, considerable more power is taken from the power source. ______
   D. In general, there is less interference heard in the receiver due to noise. ______

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MOTOROLA

RADIO COMMUNICATIONS

service

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-2
FM RECEIVERS

Receiver Block Diagram Analysis

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-2
FM RECEIVERS

Receiver Block Diagram Analysis

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

THE FM COMMUNICATIONS RECEIVER

BLOCK DIAGRAM ANALYSIS

LESSON RA-2

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Two-Way Radio has saved many lives and much property value by permitting the fire chief to direct and coordinate all fire fighting efforts at the scene as well as remain in contact with headquarters for instantaneous response to requests for aid. Fire Two-Way Radio can also lower insurance rates, and save tax dollars.

THE FM COMMUNICATIONS RECEIVER
BLOCK DIAGRAM ANALYSIS

Lesson RA-2

Introduction

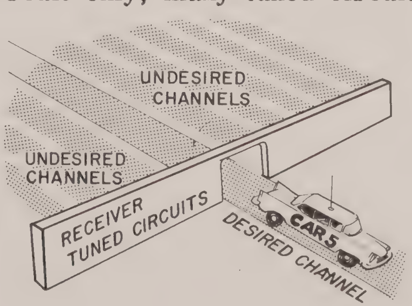
In the previous lesson we studied the nature of the frequency-modulated wave and learned how the audio modulating signal controls the extent of the carrier frequency deviation, as well as the rate of deviation. We also learned of the advantages of FM in two-way communications, the principal one being its inherent noise-free reception.

In this lesson we shall make use of several block diagrams as we continue our study of the communications receiver. We shall determine the purpose of each stage within the receiver and learn how each stage must function. After this, we shall be prepared to study the individual sections of the receiver. This lesson is confined to the single question, "What happens?" The answer to "How is this accomplished?" will be taken up in later assignments. In these early lessons, power supply considerations will be omitted. This permits simpler diagrams, so that your attention can be confined to the particular circuit under discussion. (Various types of power supplies, together with their operation, are included in the next, section of the training.)

Receiver Requirements – The "Superhet"

In order to provide interference-free operation a receiver must have three characteristics: selectivity, sensitivity, and fidelity.

Selectivity is the ability of a receiver to separate the desired signal from all others. The average receiving antenna may intercept hundreds of radio waves, each producing a voltage at its own frequency. All these RF voltages are transferred from the antenna to the receiver input and it thus becomes necessary to select the desired signal, rejecting all others, before any of these signals reach the detector. This is not accomplished in a single stage, nor in one circuit only; many tuned circuits



Selectivity in a Receiver is the Ability of Its Tuned Circuits to Accept Only the Desired Channel Signals.

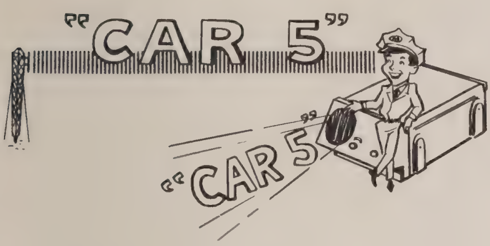
are required for this purpose. They all precede the detector, and they all have the same ultimate function--to select the desired channel. (In two-way radio practice, "channel" is the name often used in referring to the signal we want to hear. More accurately, channel refers to that portion of the radio spectrum allocated for the transmission of intelligence, and a channel is usually designated in terms of the channel mid-frequency. At the present time, channel spacings are 20 kc in the low-band (24-54 mc) and 30 kc in the high-band (144-174 mc).

The Sensitive Receiver Reproduces the Weak Signal "Loud and Clear."

Receiver sensitivity depends primarily upon the gain of the amplifier stages. Amplification alone, however, is not enough. When the received signal is very weak, it must undergo considerable amplification if the message is to be reproduced in the speaker with sufficient volume. In such cases, it may be difficult or even impossible to hear the message because of noise or interference from other stations. Sensitivity, then, also depends upon the receiver's selectivity and its ability to minimize noise. The true sensitivity of a receiver must be stated in terms of the weakest signal that can be applied at the input to produce a satisfactory output at the speaker.

Fidelity in any receiver is its ability to reproduce a message which is free from noise, interference and distortion. (Any type of interference present in the output must be considered as a form of distortion.) Receiver fidelity, then, depends on much more than the detector and audio sections. In the FM communications receiver, fidelity also depends upon the receiver's selectivity and upon its sensitivity.[1]

1. See TM 11-668 FM Transmitters and receivers, pages 114-115; also FM Transmission and Reception, by Rider and Uslan, pages 263-267.



Fidelity in a Receiver is the Ability to Reproduce an Undistorted Signal.

Because the superheterodyne receiver exhibits excellent selectivity as well as sensitivity, most of the receivers in use today are of this type. In the superheterodyne receiver--or "superhet"--incoming RF signals are converted to a lower frequency by means of a mixer. The mixer, for this reason, is sometimes called a "frequency converter." This lower frequency signal (still RF, but called the "intermediate frequency" or "IF"), is always the same for a given superhet. All superhets operate in the same way, regardless of the frequency or kind of modulation employed. Let us, then, first review the operation of the familiar AM broadcast receiver before proceeding to the more intricate FM communications type of receiver.

Simple Broadcast Receiver

Figure 1 is a block diagram of a simple AM receiver designed to operate within the standard broadcast band. The oscillator and mixer stages to the left indicate that this is a superhet. To provide for converting the incoming RF to a lower (IF) frequency, a second RF signal is generated in the local oscillator stage, and this signal combines with the RF in the mixer to produce the IF output.

Whenever two signals are combined (heterodyned) in a non-linear device, such as a mixer, a number of new frequencies are produced; for our purpose, the "difference" frequency is the one selected. A frequency of 455 kc (commonly used in broadcast band receivers) is taken as the IF in figure 1. At the same time the receiver is tuned to a station, the oscillator is adjusted so that its frequency is 455 kc higher than the incoming RF. For example, when we turn the receiver tuning knob to receive station WGN, Chicago, two things take place simultaneously. First, a tuned circuit between the antenna and the mixer is tuned to WGN's frequency (720 kc), so that maximum voltage from this station reaches the mixer grid; other signals are attenuated insofar as possible. Second, the oscillator is adjusted to generate a signal of 1175 kc, which is 455 kc higher than the RF.

The RF signal of 720 kc and the oscillator signal of 1175 kc are both applied to the mixer, and the difference or IF frequency becomes available in the plate circuit. Now, a most important factor in mixing two signals is that any modulation present on either or both of the applied signals will be present also in the IF output waveform.

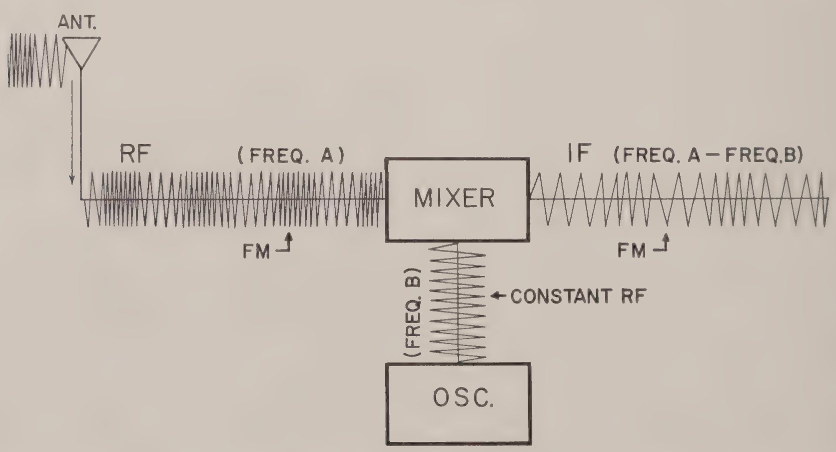
Since the oscillator waveform in this case is an unmodulated RF, the only modulation on the IF signal is the modulation of the incoming RF signal.

The advantages of selectivity, sensitivity, and fidelity which pertain to the superhet type of receiver are the result of converting the RF to this lower frequency IF signal. Since the receiver's IF stages operate at the same frequency for all incoming signals, these stages have fixed-tuned circuits, with controlled selectivity. All desired signals thus receive the same amount of amplification and are subjected to the same degree of selectivity. The selectivity of the IF amplifier is much greater than would be possible at the higher frequency RF level. The problems of feedback, too, becomes simplified, and the IF amplifier is more stable in operation.

While most of the selectivity in the superhet receiver is realized in the IF section, there must also be some rejection of unwanted signals at the RF level. Without RF selectivity the receiver will be subject to image frequency response.

Besides the desired RF, another frequency--the image frequency--can combine with the oscillator voltage in the mixer stage to produce the IF frequency of the receiver. Thus, it is essential to reject undesirable signals before they reach the mixer; this is RF selectivity.

For broadcast receivers, where the oscillator is always higher than the RF, the image frequency will be 455 kc above the oscillator frequency. For higher frequency receivers the oscillator may operate below the RF, in which case the image frequency will be below the RF and the oscillator.



In the Superhet Receiver the Incoming Signal "Beats" Against Another (Oscillator) RF Voltage in the Mixer to Produce the Lower-Frequency IF.

As an example of image frequency for the broadcast receiver, consider the previous example where the receiver is tuned to station WGN, 720 kc. With an IF of 455kc, the oscillator operates at 1175 kc. Now suppose that a strong station in the vicinity of the receiver is transmitting at a frequency of 1630 kc. If the signal from this transmitter reaches the mixer stage--not having been sufficiently attenuated in the tuned RF circuit--it will heterodyne with the oscillator to form a difference frequency. The difference frequency is 455 kc (1630 less 1175); it will be accepted in the IF circuits.

The separation between the image frequency and the RF to which the receiver is tuned is always equal to twice the IF frequency. Whether the image is above or below the RF, is determined by the oscillator. If the oscillator is above the RF, so is the image; if the oscillator is below, the image will also be below. In the broadcast receiver, the separation of 910 kc (twice 455kc) for the image is satisfactory for the tuning range of the receiver. In order to provide good image rejection in high-frequency receivers, the image must be further separated from the RF. This requires the use of a higher IF frequency.

The detector following the IF amplifier stage recovers the audio signal from the amplitude-modulated IF signal. For AM detection, the diode detector is the most

Typical Installation of a Mobile Two-Way Radio in the Trunk of an Automobile. The Speaker, Microphone and Control Head are Located Near the Driver.

practical since it is economical and has relatively little distortion. The audio voltage from the detector is too weak to operate the speaker, so an audio amplifier section is included to boost the signal power to a level sufficient for this purpose. The principal requirement of the detector and audio stages is that all distortion must be held at a minimum.

Basic FM Receiver

The basic FM receiver shown in figure 2 is not much different from the arrangement of figure 1. The oscillator, mixer, IF amplifier and audio sections are almost identical both in purpose and operation. The outstanding differences between the two receivers are (1) the type of detector required, and (2) the addition of a limiter stage in the FM receiver.

Because commercial FM signals are transmitted in the frequency range of 88-108 mc, the tubes and circuitry of the FM receiver will

differ somewhat from that of the AM broadcast receiver just described. Also, in order to prevent image frequency response, the IF is usually 10.7 mc instead of 455 kc. The strength of the average FM signal reaching the receiver is also less than that in the AM receiver. Hence, the IF section of the FM receiver usually includes two or more stages of high-gain amplification. This additional amplification is also necessary for proper operation of the limiter (which follows the IF amplifiers).

must be free from any amplitude variations--noise pulsations in particular. It is the function of the limiter to provide just such a signal.

The effect of the limiter on the IF waveform is illustrated in figure 3. The FM waveform at the left contains not only the desired signal, but many amplitude variations as well, most of them being made up of sharp pulsations of noise voltage. The waveform at the right shows the FM output from the limiter. It will be noted in this output

Limiting Removes All of the Noise Peaks from the Waveform, Thereby Producing a Constant-Amplitude IF Wave.

waveform, that all amplitude variations have been eliminated. The amplitude of each cycle remains constant and the only remaining modulation consists of the frequency variations--these have not been disturbed by the limiter. Regardless of the strength of the incoming signal to the limiter, the output voltage cannot exceed certain limits which are designed into the limiter stage. Assuming that the IF amplifiers have suffi-

Before inspecting the limiter further, let's look briefly at the FM detector. Most communications FM receivers make use of a discriminator, because of its relatively high audio output (sensitivity) and its fidelity. This same discriminator, however, is also affected by amplitude changes and its output will be noisy unless all amplitude variations have been eliminated from its input. Thus, the signal to the discriminator

cient gain, even the weakest of signals at the antenna will result in a strong input to the limiter. Consequently, all signals reaching the discriminator are equal in amplitude. The effectiveness of the limiter stage in reducing or eliminating amplitude variations (noise) from the signal depends directly upon the strength of the signal applied to that limiter. In practice we say that strong signals "saturate" the limiter. This action is considered more fully in a later lesson.

The FM detector (discriminator) of figure 2 recovers the audio intelligence from the incoming frequency deviations by converting these deviations into corresponding voltages. (The action is much the same as for the FM detector described in the preceding lesson.) The discriminator audio output is then amplified in the audio section of the receiver and the message is reproduced in the speaker.[2]

FM Communications Receiver — The Double Superhet

Before the second world war not too much was known about high frequency equipment and operation, as we know it today, and two-way mobile communications was restricted to a 30-40 mc range.

After the war the 152-162 mc range was released by the FCC for mobile applications, and it was not long before this band became popular for reliable, short-range communications. For convenience, the term "low-band" is often used to designate the lower frequency band, now expanded to 24-54 mc, and "high-band" to designate the upper range, which now covers from 144 to 174 mc. By 1952 the state of the art had progressed still further and mobile systems in the 450-470 mc range were in operation. For convenience we usually refer to this band as just "450 mc."

Figure 4 is a block diagram showing a high-band FM communications receiver designed to operate at 172 mc, but the same arrangement could be used in connection with a low-band (24-54 mc) or a 450 mc receiver. The same general pattern will apply to any communications receiver, regardless of its operating frequency. Notice that there are two oscillators, two mixers, and two IF sections. This type of receiver is called a "double" superhet. The incoming RF is first converted to a high-frequency IF for improved image-frequency rejection; then the signal is again converted, this time to a low-frequency IF, to permit greater amplification and selectivity. We can best see the action and advantages of the double superheterodyne by following the signal through the receiver.

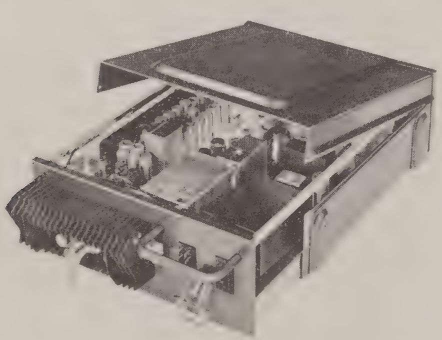
Incoming signals from the antenna first encounter an RF amplifier stage. Because of the high frequency of the incoming signal, it is not practical to expect a great amount of gain and selectivity in this stage. By carefully designing the RF amplifier, however, satisfactory rejection of unwanted sig-

2. See TM 11-668 FM Transmitters and Receivers, pages 114 and 115.

nals is possible, and the gain of a single pentode amplifier stage may be between 5 and 10. Noise generation within the stage must be kept to an absolute minimum, since any noise generated within the RF amplifier is amplified along with the signal and may interfere with reception.

A properly designed RF stage can be expected to apply a stronger signal to the mixer. At the same time, there is some rejection of unwanted signals, particularly the image frequency.

At the mixer, the RF signal combines with the 160 mc signal from the oscillator to produce the first (or high frequency) IF of 12 mc. This comparatively high value of IF places the image frequency far enough away from the channel frequency to be rejected in the tuned RF circuits. With the oscillator operating below the RF, the image will be 12 mc below the oscillator frequency, or 148 mc.



Inside this Two-Way Radio we see the Power Supply at the Right, the Transmitter in the Center, and the Receiver at the Left.

The most important requirement for the oscillator is stability, and the most stable oscillator known today is the crystal controlled oscillator. Crystal oscillators at 160 mc are not practical at the present time for use in mobile equipment, so an oscillator of 32 mc is employed and the fifth harmonic of 32 mc is selected to provide the desired 160-mc signal. This receiver is required to operate on only one frequency; hence all the tuned circuits are fixed-tuned. This affords greater efficiency and circuit stability.

The 12-mc IF signal combines at the second mixer with the 12.455 mc signal from the second oscillator (also crystal controlled) to produce the second (or low-frequency) IF of 455 kc. A second image frequency, made possible by the second mixer, must be rejected in the 12-mc IF section. With the second oscillator operating at 455 kc above the 12-mc IF, the image frequency at the second mixer will be 910 kc above 12 mc, or 12.910 mc. Since the 12-mc signal from the first mixer encounters highly selective tuned circuits in the IF amplifier stage before reaching the second mixer, the 12.910 image frequency is rejected in the 12-mc tuned circuits. [3]

Selective Filter

While the RF and first IF sections are efficient in rejecting the image and other undesired frequencies, their relative selectivi-

3. See TM 11-668 FM Transmitters and Receivers, pages 114 and 115.

Without a Squelch Circuit the Two-Way Communications Receiver Would be Very Noisy Between Messages. A Squelch Circuit "Silences" the Receiver So that the Noise is Not Heard.

ty at these high frequencies is not sufficient to reject signals of neighboring channels, which must be eliminated before they reach the discriminator. By employing a low-frequency second IF (455 kc), sharper selectivity thus becomes possible. Because the use of conventional tuned transformers does not meet the requirements of the modern communications receiver, and because the conventional tuned circuit presents the problem of alignment, Motorola has developed a highly-selective, permanently-tuned, low-loss filter which is inserted immediately following the second mixer. This filter has numerous circuits permanently tuned to the IF frequency and passes all the deviations within the operating channel, but rejects all signals outside the channel. (More will be said about this filter when we begin our study of the last IF section.)

Since the selectivity of this filter determines the ultimate selectivity of the receiver, the low IF stages which follow the filter have the sole function of amplifying the signal. The three high-gain IF stages provide far more than the minimum gain required, thus introducing a "reserve gain", which is so essential for continued receiver sensitivity over a prolonged period.

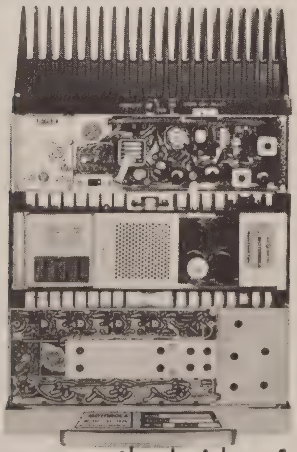
Following the second IF section are two limiter stages which eliminate any amplitude variations or noise pulsations which may be present. The input to the discriminator is then a pure FM signal containing only the deviations imparted to the wave at the transmitter. The discriminator recovers the audio component from the FM variations and its audio output is applied through two audio amplifier stages to the speaker.

Squelch

In a commercial FM broadcast receiver, the transmitter carrier is present even though the modulation may be temporarily discontinued. In the case of the communications receiver the situation is different--the carrier is present only when a message is being transmitted. During the intervals between these messages the carrier is removed. In the absence of any RF to provide this quieting,

noises entering the receiver as well as noises generated within the receiver itself cause an objectionable noise or "hiss" in the speaker. This is particularly bothersome when the receiver must be monitored constantly. A squelch circuit quiets the receiver between transmissions by preventing the noise voltages from passing through the audio stages and reaching the speaker.

As shown in figure 4, the squelch system operates into the first audio amplifier, preventing that tube from functioning. Without an incoming signal (between transmissions), the noise cannot get through the audio stage to the speaker. As soon as a signal is received, however, the squelch circuit becomes inoperative and the audio works normally. The squelch circuit controls the bias on the audio amplifier so that it operates only when a signal is coming in. At other times (when the carrier is removed) the audio stage is biased beyond cutoff and is inoperative.



Here we see the Insides of a Modern Two-Way Radio. The Transistorized Receiver is at the Bottom, the Transistorized Power Supply in the Center, and the Transmitter is at the Top.

Two-Frequency Operation

Certain applications require the communications receiver to operate on either of two frequencies. This can be accomplished by employing two oscillators at the first mixer but it is not advisable to operate two oscillators into the same mixer at the same time in an effort to receive two signals simultaneously--the receiver becomes susceptible to many spurious responses.

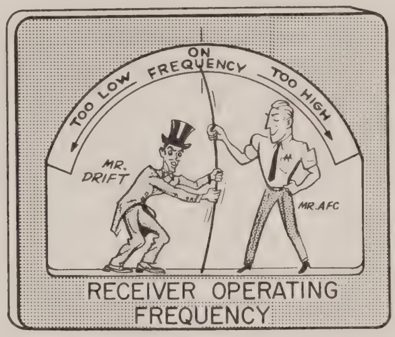
Figure 5 shows a practical arrangement for two-frequency operation. There is a minimum number of additional parts and yet the operation on either channel is excellent. Two separate crystal-controlled oscillators are required, one for each channel. Depending upon which channel is to be received, the correct oscillator is placed in operation by completing its cathode circuit to ground through the switch. For example, when the switch is at channel 1 the 160 mc oscillator is operated; when the switch is at channel 2, the 160.12 mc oscillator is operated.

This receiver will operate on either 172 mc or 172.12 mc, both of which will be picked up by the antenna. Because these two frequencies are comparatively close together, they are both amplified

in the RF stage, and the receiver operates equally well on either channel. (The frequencies may be spaced as much as 500 kc apart, but the RF circuits must be tuned to the middle frequency. For two frequencies further apart, there will be some degradation.)

When the switch is at channel 1 (172 mc), the 160-mc oscillator is operating. The 172-mc signal combines with this oscillator voltage to produce a 12-mc IF, while the 172.12-mc signal combines to produce an IF of 12.12 mc. Both of these IF's are accepted in the first IF stage and reach the second mixer, where they both combine with the 12.455-mc oscillator voltage. While the 12-mc IF produces a second IF of 455 kc, the 12.12-mc input produces an IF of 335 kc. The 455-kc IF (which represents the 172-mc signal) passes through the filter and the rest of the receiver, but the 335-kc IF (representing the 172.12-mc signal) is far beyond the frequency limits of the 455-kc filter, and this signal does not get through to the last IF amplifier.

When the switch is at channel 2 (172.12 mc), the 160.12-mc oscillator is operating; now, only an RF of 172.12-mc will produce the correct IF of 455 kc at the second mixer and reach the last amplifier. The unwanted 172-mc signal produces an IF of 575 mc at the second mixer and is rejected by the filter.



An Automatic Frequency Control (AFC) Circuit Keeps the Receiver Frequency "In Step" with the Incoming Signal.

Automatic Frequency Control

Earlier in this lesson we mentioned three frequency ranges for most mobile FM communications. At the two lower frequency ranges the use of a crystal oscillator provides ample frequency stability, and reliable operation is achieved. At 450 mc, however, the situation is somewhat different. A small frequency change at the oscillator becomes a large change at the high-frequency mixer, due to the high order of multiplication, and may not allow continuous operation under all conditions. While the circuit of figure 4 uses the fifth harmonic, it is not uncommon for a 450-mc receiver to use the 12th harmonic. Besides this change at the receiver, the transmitter may have a similar frequency variation. It is evident that something must be done to hold the receiver oscillator near the transmitter frequency.

To insure satisfactory operation of the receiver, a system of automatic frequency control (abbreviated AFC) is used. Even though the oscillator is crystal controlled, it is still possible to shift its frequency to some extent by changing the capacitance or inductance of its tuned circuit. Automatic frequency control swings the receiver oscillator close to the correct frequency. The arrangement is shown in figure 6.

The frequency control tube is a DC amplifier. Its output circuit is arranged so that the stage acts as a variable capacitance in the oscillator tank circuit. The effective capacitance changes according to the tube conduction or plate current, and this in turn may be controlled by altering the value of the DC grid bias. All that is missing now is a circuit that reacts "voltage-wise" to frequency changes.

From preceding discussions we know that the FM discriminator changes frequency variations into voltage variations. We utilize this discriminator output as a source of control voltage for the AFC control tube. In this case, we are not interested in the normal variations of the incoming signal; instead, we require a voltage that indicates the center (or average) frequency. A filter (not shown in figure 6) evens out the discriminator voltage to an average DC value. When the local oscillator frequency is correct, the discriminator output is zero. When the local oscillator is off frequency (or if the transmitter frequency should drift), the discriminator output becomes either positive or negative. This voltage is applied to the frequency control tube and changes the conduction of the stage, which in turn changes the capacitance across the oscillator circuit and shifts the oscillator frequency nearer to the correct value.

The oscillator frequency cannot reach the exact value, for this would remove any correcting voltage from the discriminator. The system, however, serves to keep the oscillator near enough to the correct value to permit normal operation of the receiver.

The AFC system can be designed to operate over a wide range of frequency drift. However, if the AFC is given too much authority in shifting the frequency of the oscillator, there is always the possibility that the AFC circuit will respond to a signal on a neighboring channel. The interfering signal will "capture" the receiver, preventing regular messages from getting through until the interfering signal is removed.[4]

Summary

Since the FM receiver uses the superhet circuit commonly found in AM receivers, most of the stages of the FM receiver operate in the same manner as those of the AM set.

The two receivers differ as to the type of detector employed. The

4. See TM 11-668 FM Transmitters and Receivers, pages 88-90 and 175 and 176; also FM Transmission and Reception, by Rider and Uslan, pages 72-76.

detector in the AM receiver must respond to changes of carrier amplitude; the FM detector (or discriminator) must respond to changes of carrier frequency.

In order to prevent undesirable amplitude variations from reaching the discriminator, limiters are used immediately ahead of it. Also, sufficient input voltage for proper operation of these limiters must be provided by the preceding RF and IF amplifier stages.

For maximum frequency stability, oscillators are crystal controlled. In addition to crystal oscillators, receivers in the 450-470 mc band are often equipped with an AFC system in order to keep the oscillator near the correct frequency.

Without "squelch," the high-gain communications receiver is very noisy between transmissions. The squelch circuit, however, disables the audio section of the receiver during those times when there is no carrier present, and prevents noise from reaching the speaker. As soon as the carrier is received, the squelch circuit becomes inoperative and the receiver performs normally.

Finally, because of the high frequency of the incoming signals, the tuned circuits of the front-end of the receiver cannot reject all the unwanted signals; this task is performed in the low-frequency section of the receiver. The highly selective Permakay filter immediately following the second mixer rejects all signals except those of the operating channel, permitting only the desired signal to pass through the last IF section to the detector.

IMPORTANT WORDS USED IN THIS LESSON

IMAGE FREQUENCY: That undesired frequency which combines with the local oscillator at the mixer to produce a difference frequency equal to the IF frequency. The image frequency is always spaced from the desired RF frequency by an amount equal to twice the value of the IF frequency.

LIMITER: As used in the FM receiver, the limiter is an amplitude controlling device. When the input signal reaches a certain amplitude, the output voltage has reached a maximum value beyond which it cannot increase, regardless of the strength of the input.

OSCILLATOR: A device that generates AC. As used in the superhet receiver, the local oscillator provides the additional RF signal which is required in order to convert the incoming RF to a lower frequency (IF).

SELECTIVITY: The ability of a receiver to discriminate between radio waves having different carrier frequencies. The selectivity of a receiver depends upon the efficiency of its tuned circuits to pass certain frequencies with a minimum amount of attentuation which rejecting (unwanted) frequencies.

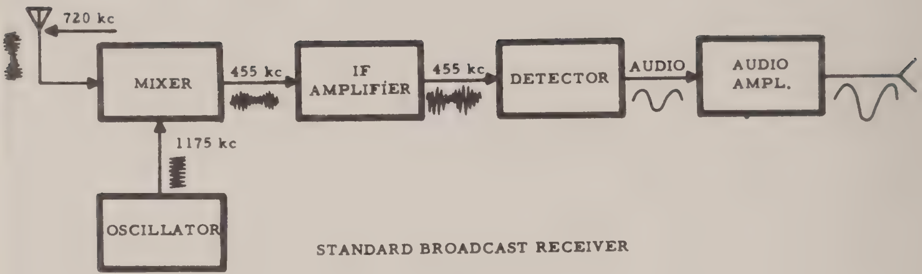
SENSITIVITY: The ability of a receiver to respond to weak signals, reproducing the intelligence satisfactorily in the output.

SQUELCH: A circuit that silences the receiver between transmissions. Without the squelch, the normally high noise level of the RF receiver produces a hiss which becomes annoying when the receiver is monitored constantly.

SUPERHETERODYNE RECEIVER (SUPERHET): A receiver which uses a local oscillator and mixer to convert all incoming signals to a lower (fixed) frequency known as the intermediate frequency (IF). The fixed-tuned circuits at the IF level allow for greater amplification, stability and selectivity.

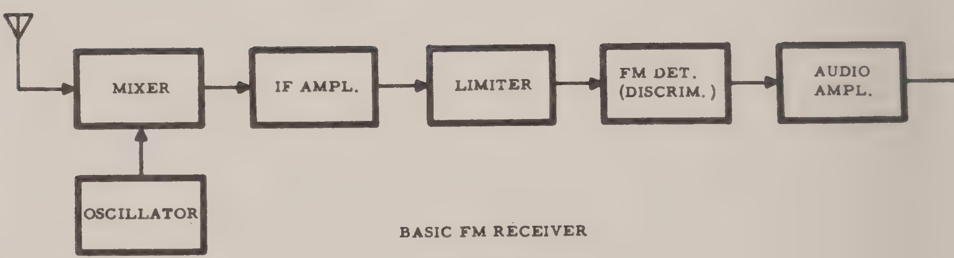
STUDENT NOTES

STUDENT NOTES



STANDARD BROADCAST RECEIVER

FIGURE 1.



BASIC FM RECEIVER

FIGURE 2.

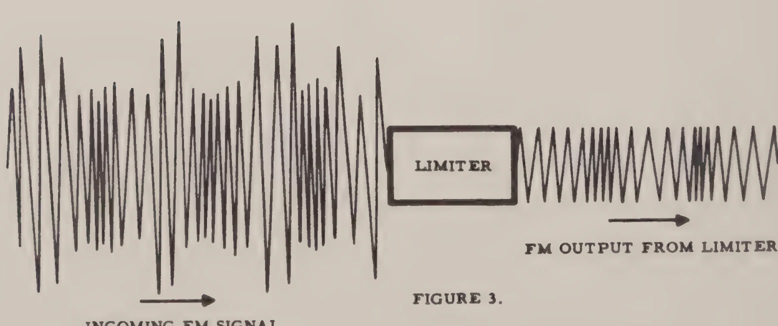
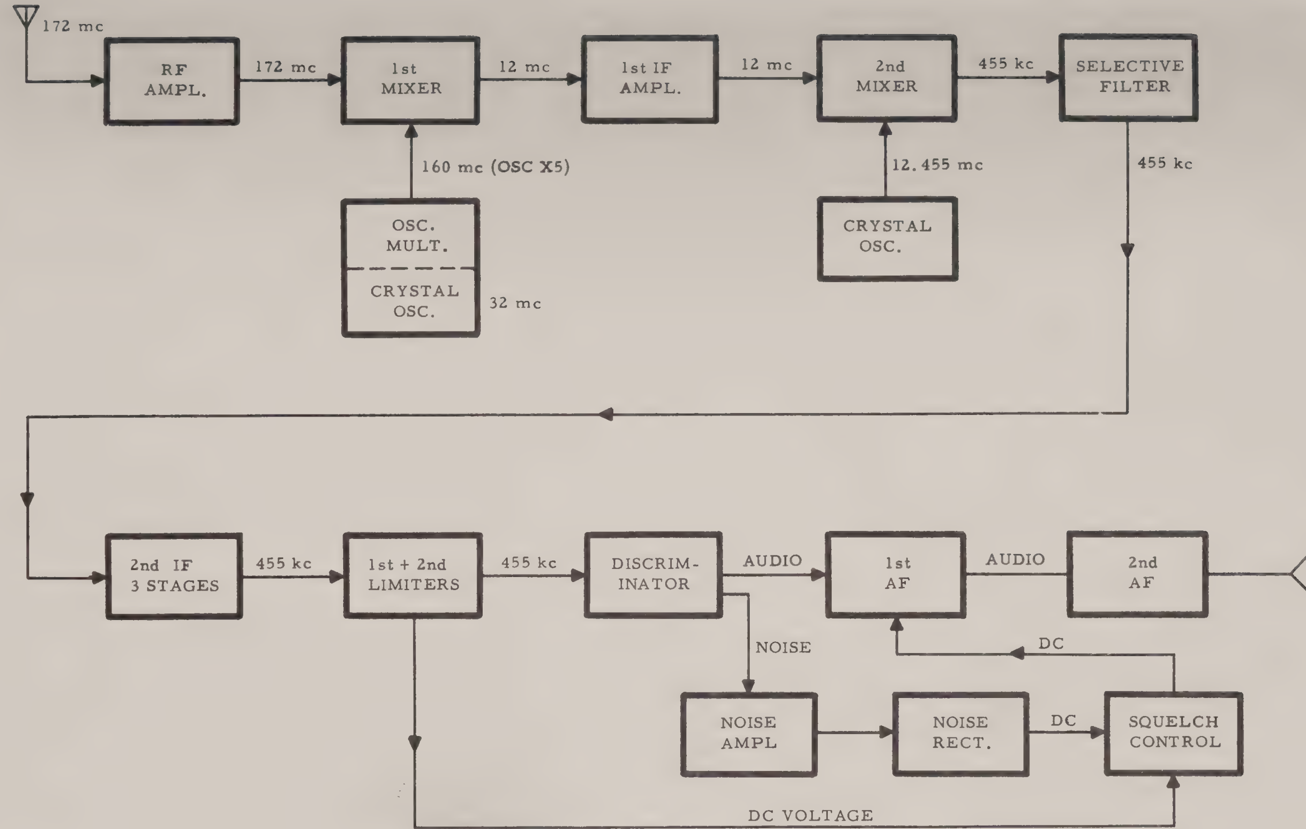


FIGURE 3.



BLOCK DIAGRAM - COMMUNICATIONS RECEIVER

FIGURE 4

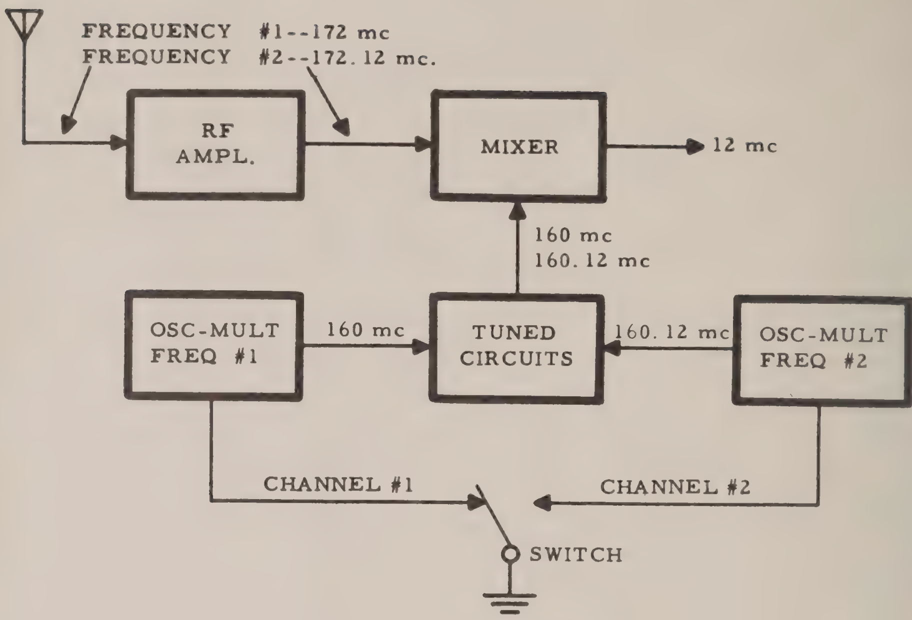
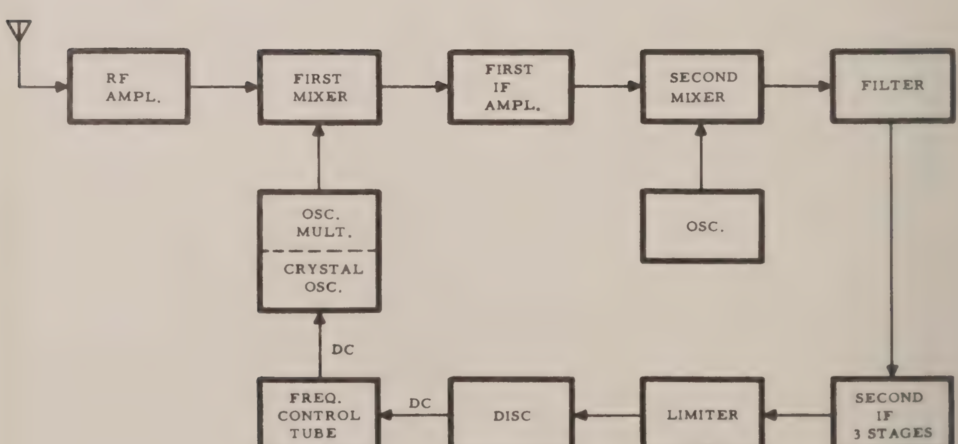


FIGURE 5

RECEIVER OPERATION FOR TWO FIXED FREQUENCIES



AUTOMATIC FREQUENCY CONTROL

FIGURE 6

Motorola Training Institute
4501 West Augusta Blvd., Chicago 51, Ill.

Please PRINT or use STAMP.

Name ______________________________ Student No. ______

Street ________________ Zone ____ Date ______

City ______________ State ________ Grade ______

EXAMINATION LESSON RA-2

1. In order to produce an IF signal in a receiver, which of the following are required:

   A. A mixer. ______________ D. An RF signal. ______________
   B. A local oscillator. ______________ E. A squelch circuit. ______________
   C. A limiter stage. ______________ F. A discriminator. ______________

2. A receiver is intended to operate at 150 mc, and the IF frequency is 8 mc. What is the correct local oscillator frequency?

   A. 166 mc. ______________ C. 136 mc. ______________
   B. 142 mc. ______________ D. 126 mc. ______________

3. A receiver is designed to receive signals of 150 mc, and its local oscillator is 138 mc. What is the image frequency?

   A. 162 mc. ______________ C. 126 mc. ______________
   B. 12 mc. ______________ D. 174 mc. ______________

4. Write "true" or "false" at each of the following statements:

   A. The squelch circuit acts to prevent noise from reaching the speaker between messages. ________
   B. The squelch circuit stops the audio section of the receiver from operating only when there is no signal coming into the receiver. ________
   C. The limiter of an FM receiver acts to reduce the noise heard in the speaker when a message is being received. ________
   D. For good limiting action, the signal amplitude at the limiter should be small compared to the noise voltages. ________

5. Check <u>all</u> correct answers. Automatic frequency control (AFC):

   A. Keeps the local oscillator near the correct frequency. ________
   B. Operates from the DC output voltage of the discriminator. ________
   C. Changes the frequency of the local oscillator. ________
   D. Keeps the transmitter from drifting too far off frequency. ________

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MOTOROLA
RADIO COMMUNICATIONS
service

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-3
FM RECEIVERS

RF Amplifier

MOTOROLA TRAINING INSTITUTE

LESSON RA-3
FM RECEIVERS

RF Amplifier

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

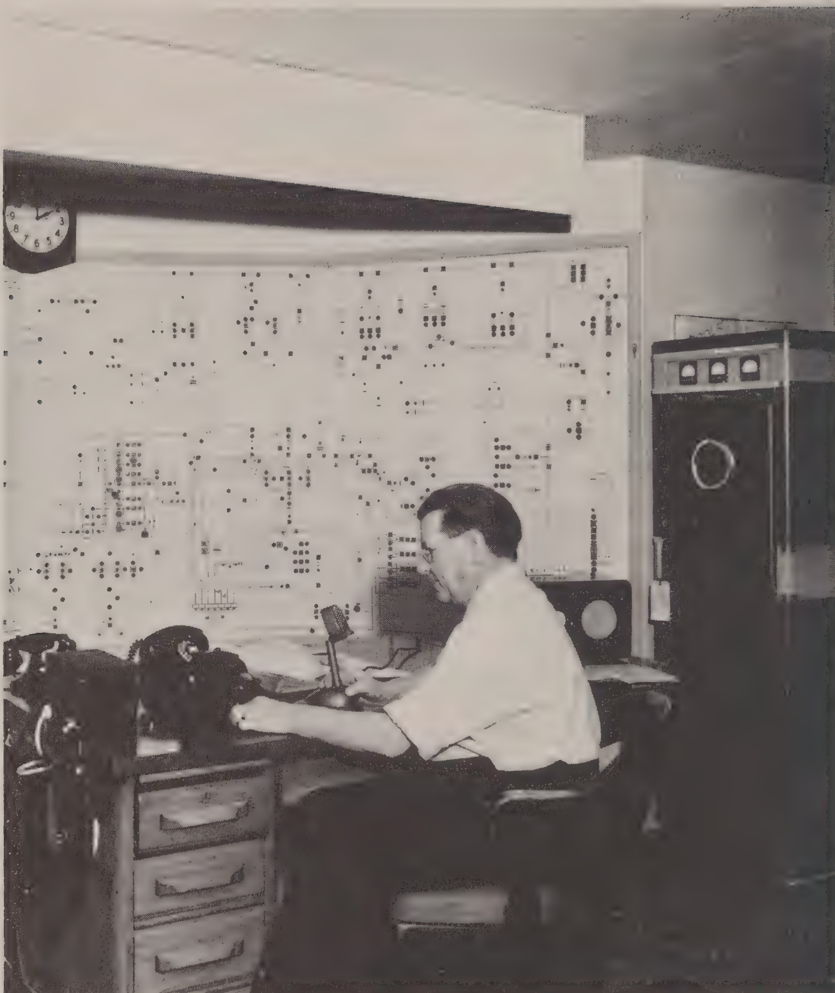
This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

THE RF AMPLIFIER
LESSON RA-3

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.



Public Utilities have greatly improved their service by equipping emergency, maintenance and construction crews with two-way radio. With trial installations made as early as 1940, they were among the first to be recognized by the FCC as an essential user of mobile radio.

THE RF AMPLIFIER

Lesson RA-3

Introduction

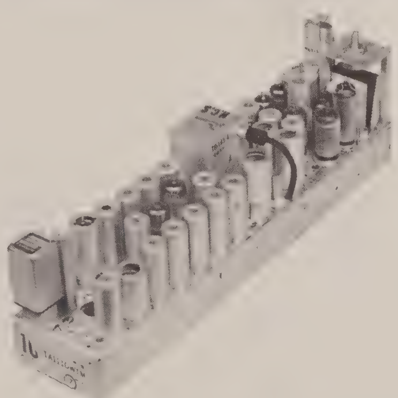
In discussing the advantages of FM over AM for two-way communication, we studied the FM wave and we saw, in lesson 1, how audio modulation causes the RF carrier to vary in frequency according to the amplitude and frequency of the modulating signal. The FM communications receiver was discussed in lesson 2 and block diagrams were used in connection with our study of the purpose and overall operation of each stage.

We shall now proceed to analyze the complete operation of the various stages within the receiver, beginning in this lesson with the RF amplifier stage. Our discussion will be concerned mainly with amplification, selectivity and "noise". We shall also discuss the class of operation and study the automatic gain control circuit which is often found in the RF section of the communications receiver.

Requirements of the RF Stage

RF stages are used extensively in receivers, both low-band and high-band. At 450 mc, however, it is difficult to provide much amplification with ordinary tubes and circuitry. Receivers in this and higher frequency ranges often incorporate a highly selective filter to provide the necessary selectivity, but otherwise apply the signal directly to the mixer.

Where an RF stage is used, efficient operation depends upon the ability of that stage (1) to reject interfering signals as far as possible by incorporating sharp RF selectivity, and (2) to establish the best possible signal-to-noise ratio at the mixer input by providing an optimum amount of



High-Band Receiver Chassis of the Type Used in Two-Way Radio Systems.

amplification. The undesired signals which must be rejected include the image frequency, those at the intermediate frequency of the receiver, and all others which might cause interference. (More will be said about interfering signals later in this lesson).

While circuits are effective in rejecting undesired signals, they also cause some insertion loss (attenuation of the desired signal). The RF gain, however, more than compensates for this loss, with the result that the amplified signal at the mixer establishes a better signal-to-noise ratio--better than when the signal is applied directly from the antenna to the mixer.

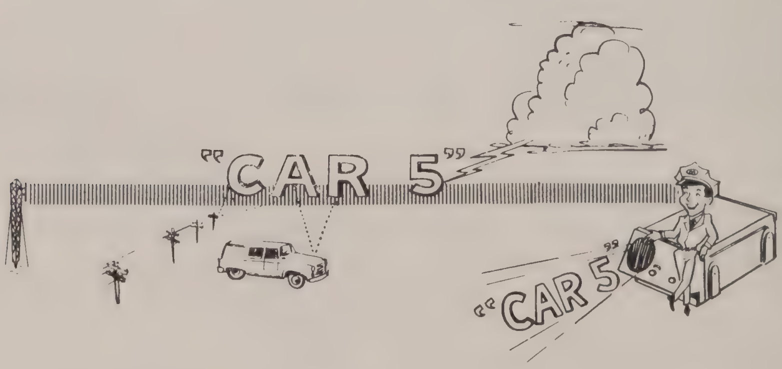
In the design of the RF stage--particularly in the choice of the RF tube--attention must be given to the amount of noise generated. Unless this noise is held to a minimum the signal-to-noise ratio will suffer, resulting in a decrease of receiver sensitivity.

The RF stage must also (1) provide an impedance match between the antenna circuit and the RF grid circuit, and (2) isolate the antenna from the local oscillator. (Oscillator energy reaching the antenna will radiate into space and interfere with the operation of other receivers in the vicinity.)[1]

Now that we know the requirements of the RF stage, we are ready to begin our study of this section of the receiver. We will start by discussing the signal-to-noise ratio.

Signal-To-Noise Ratio

Small signal voltages entering the receiver must compete with any noise in the receiver; and the total noise, whether external or internal in origin, limits the small-



Interference Does Not Affect the Strong Signal. The Large Signal-to-Noise Ratio Yields Noise-Free Reception.

[1]See TM 11-668 FM Transmitters and Receivers, page 116; also FM Transmission and Reception, by Rider and Uslan, pages 251-256.

est signal voltage which can be successfully received. It therefore becomes important to have some means of comparing the strength of the signal with that of the noise.

the signal undergoes the required amplification in the RF stage, the relatively high noise level of the mixer will limit the receiver's sensitivity.[2]

Interference Overrides the Weak Signal. The Small Signal-to-Noise Ratio Results in a "Noisy" Output.

The expression "signal-to-noise ratio," which is usually abbreviated "s/n ratio", is used to compare the strength of the desired signal with the noise voltages present in a particular circuit. The s/n ratio is most important at the input of the receiver, where the signal level is low. Unless the incoming signal voltage is greater than the noise voltages, satisfactory reception usually is not possible. The amount of noise present at the receiver input, together with the noise generated within the RF circuitry, determines the weakest signal that can be received.

Also, while the RF stage itself generates a certain amount of noise, the mixer which follows the RF stage is an even greater offender in this respect. Unless

Because noise plays such an important part in determining the overall performance of the receiver, let us digress briefly at this point for the purpose of examining the nature of this noise before proceeding further with our discussion of the RF stage.

Noise Sources and Noise Frequencies

Noise may be either external or internal, according to whether it is man-made, natural, or generated within the receiver itself. It may be either impulse noise or random noise according to its waveform, and it may also be classified, to some extent, as to frequency.

Noise may enter the receiver

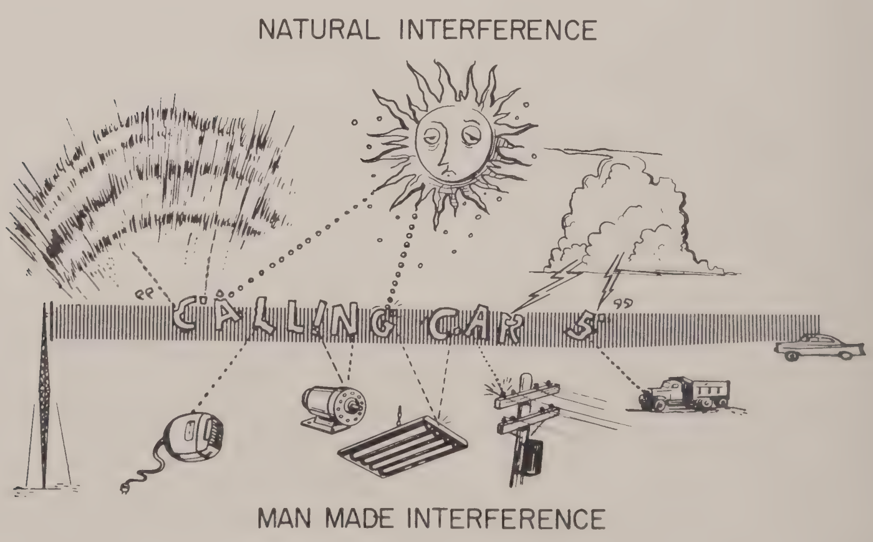
[2] See FM Transmission and Reception, by Rider and Uslan, pages 251, 254-255.

from some external source, in which case it may be either man-made or due to natural causes. Noise may also be internal in origin, since it may be generated within the receiver circuits and their components. Noise, particularly man-made noise, is not distributed uniformly throughout the frequency spectrum. Impulse noise is most bothersome at frequencies from approximately 15 to 160 mc, while random noise is generally considered to cover all frequencies.

First, let us consider man-made noise, after which we shall then proceed to examine natural noise and receiver noise.

Man-Made Noise

Man-made noise falls within the two general classifications mentioned above, (1) impulse noise and (2) random noise. Impulse noise consists of sharp pulses of RF voltage, which produce audible pulses (sound) at the speaker. These noise pulses are often hundreds of times greater in amplitude than the signal and may make it impossible to hear the desired message. The most common source of impulse noise is the ignition system used with gasoline engines. Because two-way radio



"Interference" in the Radio System Has Many Points of Origin.

is predominantly vehicular, impulse noise is a major problem. Preventive measures are taken to eliminate as much of this noise as possible, but there is always a small component of noise left which may interfere with the reception of weak signals.

The second kind of man-made noise (random noise) is more continuous in nature. It appears as a broad band of many pulses which bear little or no relation to each other. Such noises are produced by rotating electrical machinery, automotive generators and regulators, high-voltage power transmission lines, gas rectifiers and similar devices.

Man-made noises can reach the receiver in several ways. It can be received as a radiated signal along with the desired signal. Or power lines, in the vicinity of the receiver antenna and to which a noise producing device is connected, may induce noise voltages directly into the antenna. Or, in fixed installations where operation is from power lines, noise may enter the receiver directly from these power lines. This is sometimes called "conducted noise".

Natural Noise

Natural noise arising from various sources frequently proves disturbing to radio communications. Such noise may be of either the impulse or the random type. Perhaps the most familiar example of natural noise is that produced by lightning discharge. This type of noise is not entirely due to local storms; it frequently originates in the tropical storm centers and then it is propagated as a radio wave to many parts of the earth. The highest noise levels are usually encountered during our summer months. Fortunately, the intensity of this noise is less above 40 mc, where most two-way communications take place. Some noises are attributed to sun-spots and other natural phenomena. Nothing can be done about natural noises at their sources.[3]

Receiver Noise

In addition to man-made and natural noises entering the receiver from the outside, noises are also generated within the receiver itself. Almost all noises generated within the receiver are of the random type, for they are continuous, have no specific waveform, and cover a wide range of frequencies.

One source of receiver noise is the irregular electron motion within any current passing through a conductor. This erratic motion of electrons causes small variations in the current and a corresponding change in voltage. This is called "fluctuation noise" and has no specific waveform or frequency.

Another source of noise is the normal but haphazard motion of atoms, and molecules, and elec-

[3]See TM 11-668 FM Transmitters and Receivers, pages 116-117.

trons. These particles make up all matter. They are always in violent motion and their activity increases with temperature. The resulting noise (designated as "thermal" noise) is present in any circuit containing resistance.

The amount of noise generated in the input circuit of a receiver is determined by the bandwidth and impedance of the circuit. A circuit designed to operate on a wide band of frequencies and having a high impedance generates more noise than a circuit with a narrow band acceptance and a low impedance.

Tubes Are a Source of Receiver "Noise."

Tubes also produce considerable noise due to three distinct actions inside the tube.

1. Electrons leave the cathode at irregular intervals and with random velocity. Their arrival at the plate is also irregular and causes noise pulsations in the plate circuit. This is known as the "shot effect".

2. Electrons leaving the cathode of a pentode or other multi-element tube form separate currents on their way to the plate and screen. This division of the electron stream is a source of noise and is most noticeable in tubes which have a number of positive grids. Such a division of cathode current does not normally take place in triodes, so these tubes are not subject to this effect.

3. Another noise generated within the tube is due to electrons passing close to the control grid on their way to the plate. Small noises are thus induced into the grid circuit and add to other noises present.[4]

Of all tube types, the triode is the "quietest". The sharp cutoff pentode is next best, followed by the remote cutoff pentode and multi-element tubes in that order. Regardless of the tube used, noise may be minimized by establishing a low value of cathode current.

Amplification Requirements

Because the mixer has an inherently high noise level, the signal voltage must be strong when it reaches this stage. (The high noise level at the mixer is due to several factors. First, the oscillator-multiplier section generates noise, and this noise reaches the mixer along with the desired oscillator signal. Second, the mixing of two different frequencies causes added variations in the electron stream within the tube--which in turn means more noise. In addi-

[4]See TM 11-668 FM Transmitters and Receivers, pages 118-119; also FM Transmission and Reception, by Rider and Uslan, pages 279-281.

tion, the conversion efficiency of any tube is low compared to the operation of the same tube as an amplifier, and the lower available output voltage at the IF frequency means a relatively low signal-to-noise ratio.) The RF section of the communications receiver must therefore provide the necessary gain in order to establish a satisfactory signal-to-noise ratio at the mixer.

An RF gain of 5 will be sufficient in most cases to produce satisfactory results in a receiver which has a well-designed mixer stage. However, for positive operation under adverse conditions a gain of 8 or 10 is more desirable. At frequencies below 200 mc, a single well-designed stage of RF amplification using a pentode is preferred to two stages of triode amplification, and the pentode will provide about the same amount of gain.

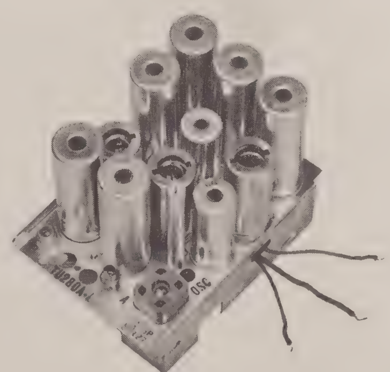
At higher frequencies (above 200 mc), the pentode becomes less satisfactory and at these frequencies triode amplifiers are generally employed. They must be neutralized, however, or used as grounded grid amplifiers; otherwise they will be unstable.

If all noise generated in the RF stage is kept to a minimum and, at the same time, the incoming signal is amplified so that the signal has the best possible s/n ratio when it reaches the mixer, the RF amplifier will have fulfilled one of its important requirements. We must remember, however, the matter of selectivity, and we shall next discuss the selectivity of the RF stage.[5]

Why Selectivity?

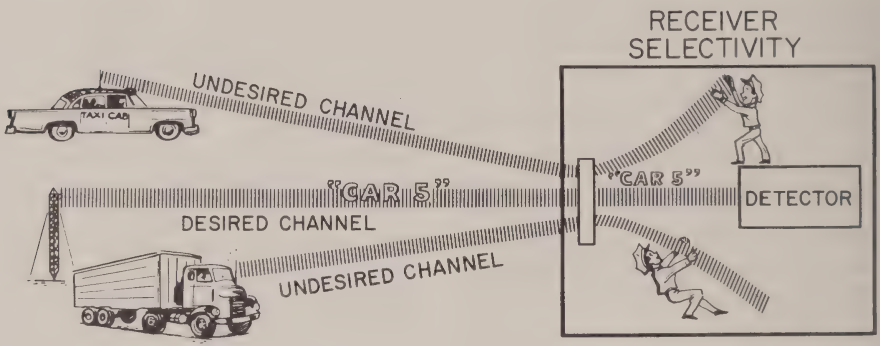
A tremendous expansion of the radio industry--two-way mobile communications in particular--has been going on for the last few decades. In the field of two-way communications, this expansion is made evident by the rapid increase in the number of installations, creating the problem of providing ample channels for their use and operation, a problem which must be solved if the threatened congestion is not to become utterly hopeless.

The number of frequencies assigned to two-way mobile communications has (like that of almost all other services) remained



Some Receivers Are Made Up of Subchassis. Here We See an RF and High-Frequency Oscillator Deck.

[5]See TM 11-668 FM Transmitters and Receivers, pages 120 and 121; also FM Transmission and Reception, by Rider and Uslan, pages 251-256.



"Undesired Channel" Signals Are Rejected By the Receiver's Tuned Circuits. The "Desired Channel" Signals Are Selected and Reproduced.

unchanged for the last several years. The number of users, on the other hand, has already become so great that competing services are often compelled to share the same operating frequency.

So much for the problem. A partial solution is seen in the possibility that additional channels may be made available in the 900-mc range, but this will not entirely relieve the congestion. The demand for more channels will continue, and it seems that the only immediate answer to the problem is to utilize the presently allocated channels to a greater degree. Receivers must be made more selective.

Communications receivers, prior to 1950, had comparatively poor selectivity. As a result, operating channels were widely spaced, and the intervening frequencies or "in between" channels could not be used without causing interference. Improved circuitry such as the highly selective receiver filter mentioned in the previous lesson made it possible to assign systems to alternate channels in the same area, and even to adjacent channels, but the problem still remained--there were fewer channels than users.

The FCC (Federal Communications Commission), aware of this demand for additional channel allocations, has ruled that the frequency band from 152 to 162 mc shall be converted to "split-channel" operation, the complete change to become effective in 1963. Instead of the present spacing of 60 kc, there will be only 30 kc between channels. By effectively doubling the number of channels, the FCC ruling improves the ratio of channels to users. On the other hand, the problem of "more signals on closer frequencies" is intensified as a result of this ruling.[6]

In order to operate on closer frequency assignments, receivers

[6] In more recent rulings, many of the channels in both the high and low bands are being converted to split-channel operation.

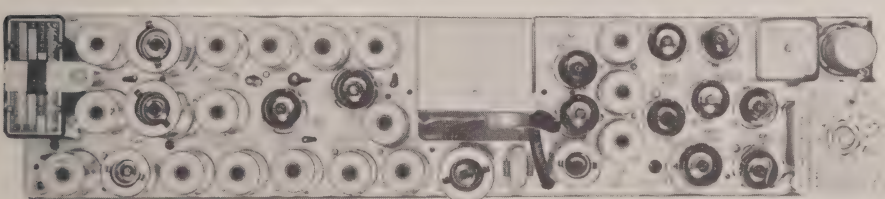
(as well as transmitters) must possess excellent frequency stability; transmitter deviation must be carefully controlled, and so must receiver selectivity. Otherwise, narrow-band operation would be impractical. In the case of the receiver RF section, there are two major problems involved in close channel spacing. One of these concerns desensitization; the other, intermodulation. Since both occur in the front end of the receiver, they must both be accorded full consideration here in connection with our study of the RF amplifier stage.

Desensitization and intermodulation are caused by unwanted signals entering the front-end of the receiver. These are not new problems, but they become more serious with additional transmissions on closer frequencies. The design and the operation of the RF section of the receiver thus become increasingly important--incoming signals which could produce desensitization and intermodulation must be rejected. The receiver, in other words, must have sharp RF selectivity.

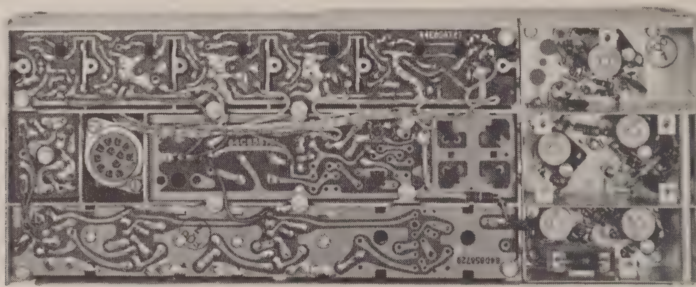
Desensitization

Desensitization can best be described by means of an example. A police squad car, radio equipped, is cruising in the vicinity of a local taxicab transmitter, operating on an adjacent channel. The strong signal from the transmitter is said to "desensitize" the police radio if it reduces the gain of the receiver. The desensitization may render the police receiver completely inoperative as long as the car is in the neighborhood and while the interfering signal is on the air. Since the desensitizing signal is eventually rejected by the selective filter, it is not heard; the squad car operator may not even know that his receiver has become inoperative! As soon as the car leaves the area, or the interfering signal goes off the air, everything is back to normal.

Desensitization is caused by the interfering signal exceeding the fixed bias on one of the amplifier tubes, with the result that the tube draws grid current on the positive peaks. This increases the bias



Top View of a Two-Frequency Receiver--See the Two Crystals at the Left. At the Far Right Is the Audio Level Control.



The Underside of a Modern Two-Way Receiver. This Receiver is Completely Transistorized and Has Modular, Printed Board Construction.

on the stage and reduces the gain. Another effect is to "load" the tuned circuits, reducing their "Q" and selectivity as well as the amplification. Desensitization is possible with only one interfering signal--this signal is usually very strong and close to the operating frequency of the receiver.[7]

Intermodulation

Intermodulation is similar to desensitization in that it is an interference due to unwanted signals which enter the receiver. Unlike desensitization however, intermodulation requires two or more signals, which combine to produce a new signal at the channel frequency of the receiver.

Intermodulation, like desensitization, can also be best explained by means of an example. Let us consider a receiver designed to operate at 152.00 mc. Entering the receiver are two unwanted signals of 152.12 and 152.24 mc. These two signals may combine in the mixer to produce a signal of 152.00. Here is how it happens. We know that among the additional frequencies created in the mixer will be the second harmonic of any incoming signal. Now the second harmonic of 152.12 is 304.24 mc, and this frequency combines with the 152.24 signal to produce a difference frequency of 152.00 mc (the operating frequency of the receiver). Any modulation present on either of the incoming signals will modulate the new frequency and be heard in the speaker. Moreover, the deviation of the 152.12 mc signal is doubled in its harmonic, increasing the interference.

The frequencies causing intermodulation are usually close to the center frequency of the receiver, although this is not essential as long as the signals are strong and reach the mixer with sufficient amplitude. Intermodulation may also take place in conjunction with commercial FM transmissions, TV stations, and even standard broadcasts. Intermodulation oc-

[7] See "Desensitization" article.

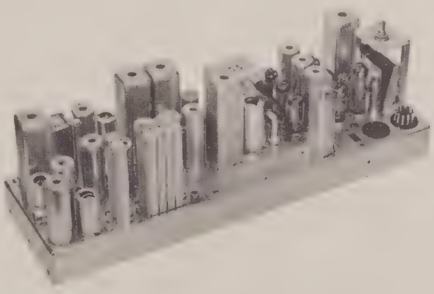
curs only when all signals causing this condition are on the air simultaneously. As a general rule, the percentage of time that all the signals are available simultaneously is fairly small; with commercial broadcasts, however, the carrier is present during the major part of the day and intermodulation effects are more continuous.[8]

Preventing Desensitization and Intermodulation

Strictly speaking, there is no practicable protection against extremely strong signals close to the operating frequency. It is possible to minimize the effects of both desensitization and intermodulation and, in certain instances, to actually eliminate such forms of interference, but the problem still exists as a challenge to efficient two-way communications, especially in the mobile field.

In recent years considerable attention has been given to good receiver design, and AGC (automatic gain control) circuits have proved to be helpful in reducing intermodulation. Great stress has also been placed upon the RF section and its ability to reject unwanted frequencies, for the very nature of desensitization and intermodulation would seem to indicate that a possible solution might be to install highly selective filters ahead of the receiver's RF stage. This would eliminate all except the desired frequency and there would be nothing to produce either desensitization or intermodulation. This procedure is not practicable, however, for two reasons. First, a sharp selectivity can be had only at the lower frequencies. At the RF frequency, it is impossible to achieve the necessary selectivity with practical tuning devices so far developed. Second, since all components have some internal losses, any tuned circuit will contribute a certain amount of attenuation, even to the desired signal. In order to achieve a reasonable degree of selectivity, numerous tuned circuits would be required and the signal attenuated to a very low level--too low to compete with the receiver noises. Such a receiver would have a poor signal-to-noise ratio on most signals and only strong signals would be heard satisfactorily.

At fixed installations, it has been possible to reject most unwanted signals by placing large but very efficient "cavities" in series with the receiver antenna leads. These cavities have a very high Q and are tuned to the frequency of the desired signal. Acting like a par-



A 450-MC Receiver Chassis, the Rectangular Units (Left Front) Are the 450-MC, Cavity-Type Tuned Circuits.

[8]See "Intermodulation" article.

Low-Band Cavity Resonator.

allel tuned circuit across the receiver input, these cavities prevent voltages at the interfering frequencies from reaching the receiver. The attenuation to the interference is very effective, but there is little loss at the operating channel. If necessary, two or more cavities may be used in series.[9]

In the case of mobile installations, the most logical solution lies in system design. One of the most effective factors is the careful selection of operating frequencies for the various services in a given locality. The FCC has jurisdiction over channel allocations and this body is very cooperative in assigning frequencies so as to avoid interference. (System engineers are competent to suggest proper frequency assignments to minimize intermodulation and desensitization.) Another factor in system design is the relocation of stationary antennas away from the immediate service area of all mobile units; most of the really serious interference is thereby eliminated.

The RF Input Circuit--Impedance Matching

It is common to call the circuit between the antenna transmission line and the RF grid the "input circuit". This circuit has two basic functions. First, being a tuned circuit, it must provide some selectivity. Second, in order to transfer maximum energy (signal) from the transmission line to the RF grid, it must "match" the impedances of these circuits.

The antenna input or transmission line usually has an impedance of 50 ohms at the channel frequency. Thus, as far as the transmission line is concerned, the input circuit must look like 50 ohms. This circuit forms a parallel tuned tank between the grid and ground, and a parallel tuned circuit usually has a high impedance.

An impedance match may be effected by several methods. One of the most common makes use of a transformer in which the primary winding impedance matches that of the input, while the secondary impedance is that required in the

[9] See "Cavity Resonator" article.

RF grid. Another method of impedance match is to use a single coil, but to connect the input to a low-impedance tap on the winding.

The Motorola circuit of figure 1 employs still another approach to the problem of impedance matching. Here the input is connected or "tapped" between two series-connected capacitors, which themselves are a part of the grid tank-circuit. This arrangement allows a step-up of voltage and impedance in the same manner as if a tapped coil were used. The value of the input capacitor is selected so that at the operating frequency its impedance is about 50 ohms; thus, the receiver input is 50 ohms. (Sometimes a slight mismatch is introduced in order to obtain an improved s/n ratio.)

The grid circuit sees a parallel tuned circuit between grid and ground, and this offers the required high impedance. For figure 1 the step-up in voltage from the antenna input to the grid is about 5 times, which means a corresponding improvement in the s/n ratio. (While the signal at the resonant frequency is built up 5 times, the noise generated remains unchanged.)[10]

The RF Amplifier Output Circuit

The plate circuit of figure 1 is rather unusual in that it makes use of three highly efficient tuned circuits. Furthermore, these tuned circuits are "critically" coupled to provide maximum gain and optimum frequency selection. Whenever several tuned circuits are used, the coupling between them greatly affects both the selectivity and the amount of signal voltage at the output. With transformers, the interaction of the coils (mutual induction) determines the amount of coupling. For the plate circuit of figure 1, the degree of coupling is determined by the value of the capacitors between the tuned circuits.

With a small degree of coupling, tuned circuits react at their natural resonant frequency and the selectivity is very good. As the coupling is increased, the output voltage continues to increase up to a certain point (called "critical coupling") beyond which there is no

Here We Find Some of the Individual Parts Used in Receiver Construction; Starting at the Bottom, We See Several Steps of Assembly.

[10]See TM 11-668 FM Transmitters and Receivers, pages 119-120.

further increase in output voltage. Increasing coupling up to the point of "critical coupling" increases the bandwidth a small amount. Beyond critical coupling, however, the bandwidth increases rapidly. This is called "overcoupling" and causes poor selectivity. In addition, the output voltage will be lower than the maximum value established at critical coupling. Thus, it is important to employ critically-coupled circuits in order to obtain good selectivity and sensitivity.[11]

In addition to critical coupling it is important to use circuits having a high Q, for this determines their ability to reject unwanted signals. High-Q circuits afford much better selectivity than those with a lower Q. At higher frequencies, such as found in communications receivers, the Q of the coil and the degree of loading determine the Q of the tuned circuit. The Q of a coil is the ratio of its reactance to its resistance. (As a formula, $Q=2\pi FL \div R$, where R is the resistance to high-frequency current traveling on the surface of the conductor.) The coils of many Motorola receivers are made from silver plated "ribbons" having a large surface area. This reduces the "R" and produces a high Q. The three critically-coupled high-Q tuned circuits in the RF stage of figure 1 provide excellent selectivity, rejecting the image frequency as well as many other signals that might cause interference. At this frequency it is impossible to reject all signals on the neighboring channels, but these are eliminated by the selective filter in the last IF section.

The RF Stage As A Class Amplifier

When it is necessary to secure good amplification with a minimum of distortion we use class A amplification. The signal voltage in a class A amplifier must not drive the grid positive with respect to the cathode, causing grid current. The tube is operated as near as possible to the center of the straight portion of its characteristic curve. A typical class A amplifier is shown in figure 2. Plate current is plotted on the vertical axis and grid voltage on the horizontal axis. The tube bias should be at the center, marked "X" on the curve. The incoming signal to the RF grid, at the bottom of the figure, varies the total grid voltage and operates the tube between points A and B on the curve. Plate current varies between A and B . If the operation is linear the output waveform is an exact duplication of the RF grid voltage. The amplitude of the signal in the plate circuit will be several times greater than the input, the exact amount depending upon the gain of the stage.

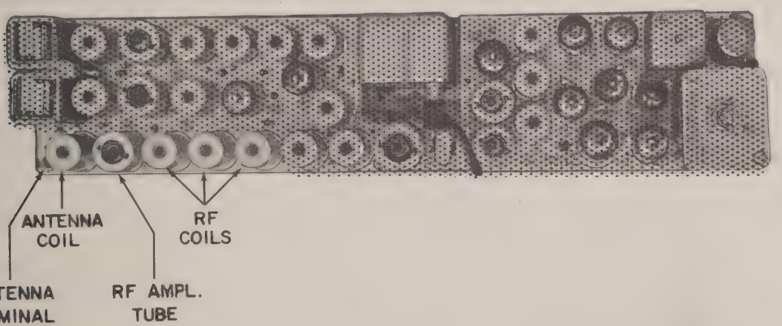
The gain of the stage in turn depends upon the grid bias. In figure 3 the bias has been increased so that the tube operates near the lower part of the curve. The value or amount of signal voltage to the grid is the same as in figure 2, but the amount of plate current change is less, which means that the sig-

[11]Coupling is discussed in greater detail in a later lesson.

nal voltage in the plate circuit is reduced. Automatic gain control circuits make use of this reduction in gain when the bias of a stage is increased. The grid circuit is returned to some source of negative voltage which varies with the signal level, and in this manner the gain of the stage changes (inversely) with the strength of the incoming signal. Let's look at this circuit a little more in detail.

er, and are less likely to cause intermodulation. Even with decreased amplification, the desired signal voltage has sufficient amplitude to produce a good noise-free output at the speaker.

The AGC circuit (omitted from figure 1) is shown in figure 4. Disregard at this time the connection to the screen of the IF amplifier, and consider the rest of the cir-



A "Parts Location" Type of Photo Used in Service Manuals. Only Those Components of the RF Section Are Identified.

Automatic Gain Control

Automatic Gain Control, or "AGC" as it is usually called, lowers the amplification or gain of the RF stage when a strong signal is received. Several advantages result from this action. First, the signal at the receiver is normally higher than the minimum value necessary to operate the receiver. By reducing the RF gain on strong signals, interfering signals receive less amplification. As a result, these undesirable voltages have a lower amplitude at the mix-

cuit. The AGC controlling voltage is secured from the grid of a limiter tube. The grid of the limiter constitutes a rectifier circuit for the applied signal, producing a negative voltage having an amplitude which is directly proportional to the strength of the signal at the limiter grid. A filter (R and C of figure 4) eliminates any RF pulses in the AGC control line, and a steady DC potential is thus applied to the RF grid. The time constant of this filter prevents sudden changes of signal voltage from reaching the RF grid.

When a strong signal reaches the receiver, the voltage at the limiter is high and causes a relatively large negative voltage at the limiter grid. This negative voltage is applied to the grid of the RF amplifier as additional bias and reduces the stage gain. A weak signal produces less voltage at the limiter grid and a smaller AGC bias is applied to the RF grid.

There is one undesirable feature inherent in this system. Even a weak signal entering the receiver will cause some negative limiter grid voltage, and the resulting AGC voltage at the RF grid will reduce the gain for this weak signal. Obviously this is unsatisfactory, for it reduces the sensitivity of the receiver on weak inputs.[12]

Delayed AGC

Let us now return to figure 4 and consider the portion which was disregarded in the preceding paragraph (the connection to the screen of the IF amplifier). To avoid the reduction of RF gain by AGC action on weak signals a system called "delayed AGC" is employed. The delaying voltage is obtained by introducing a small positive potential from the screen of an IF amplifier stage into the AGC control line. Due to "Edison Effect" (produced by the small grid current through the large grid resistor) the grid of the RF stage does not become positive but remains slightly negative.

With this arrangement, the AGC line will no longer become negative for weak signals entering the receiver; the negative voltage at the limiter grid must first overcome the positive voltage of the AGC line. When the signal reaches a certain level, the increased bias voltage at the limiter grid makes the AGC line negative. Any signal with this minimum amplitude (or greater) will cause AGC action. Thus we use the term "delayed" AGC, since AGC operation is delayed until the signal has attained a certain level. With delayed AGC, the receiver operates at maximum gain on weak signals, but still provides AGC action on strong signals and greatly improves the receiver's freedom from intermodulation.

Oscillator Radiation

The local oscillator is in reality a small transmitter, and unless it is well isolated from the antenna, considerable oscillator energy may be radiated into space. This additional "signal" is quite capable of interfering with the operation of other receivers in the area.[13]

The RF stage isolates the antenna from the oscillator. Without the RF stage, the antenna would be coupled into the mixer, and it would be relatively easy for the oscillator voltage to feed into the antenna and radiate into space. The RF stage separates the oscillator and the antenna so that less energy from the oscillator reaches the antenna. With good shielding between the circuit components and with good grounding to minimize ground

[12] See TM 11-668 FM Transmitters and Receivers, page 127; also FM Transmission and Reception, by Rider and Uslan, pages 288-290.

[13] See TM 11-668 FM Transmitters and Receivers, pages 132 and 133.

currents, the oscillator energy must feed from the grid of the mixer through the coupling circuits to the plate of the RF stage, through the tube capacitance to the grid and on through to the antenna. This path allows only a very small amount of energy to get through--far below the maximum amount permitted by the FCC.

Summary

The amount of noise at the grid of the RF stage determines the weakest signal that may be successfully reproduced. Unless the RF stage provides enough amplification, the signal cannot compete with the high noise generated by the mixer. In addition to the noises entering the receiver, noises are generated in the circuits and tubes of each stage.

The RF stage must provide some amplification of the desired signal and afford optimum selectivity; at the same time, the noise generated internally must be kept to a minimum.

The input circuit must provide an impedance match between the antenna system and the grid circuit of the RF amplifier. This is accomplished by means of a transformer or a tap on the tuned circuit.

With the increase of channel assignments in metropolitan areas the problems of intermodulation and desensitization have become serious. In an effort to eliminate all unwanted signals, the RF stage uses critically coupled, high Q tuned circuits. Also, by employing delayed AGC, weak signals receive full amplification but stronger signals encounter reduced RF gain. This limits the amplitude of unwanted signals reaching the mixer.

Thought should be given to intermodulation and desensitization when making frequency assignments and locating antennas. Large, high-Q cavities, tuned to the desired channel, may be used in the transmission line at stationary receiver installations to minimize these effects.

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IMPORTANT WORDS USED IN THIS LESSON

AUTOMATIC GAIN CONTROL: A method of controlling the overall amplification of a receiver by varying the gain of one or more stages, inversely with the strength of the incoming signal. When used with two-way FM receivers, AGC is highly effective in reducing intermodulation.

CAVITY: A device having a very high Q, used to reject unwanted energy at frequencies close to the operating frequency of the system. Used in the antenna lead of the receiver, cavities prevent intermodulation and desensitization.

DELAYED AGC: An AGC system in which weak signals are prevented from producing any AGC action. This allows the receiver to operate at full sensitivity for weak signal inputs.

DESENSITIZATION: This is the reduction in gain of one or more stages of a receiver, caused by a strong unwanted signal exceeding the established bias on that stage.

IMPULSE NOISE: Those noise voltages which have very sharp peak amplitudes and which occur at irregular intervals. The most common source of impulse noise is the ignition system used with gasoline engines.

INSERTION LOSS: The attenuation of the desired signal by some circuit element, such as a tuned circuit or filter.

INTERMODULATION: A type of interference, evidenced in receivers, whereby two or more unwanted signals combine to create a new frequency corresponding to the channel frequency of the receiver.

NOISE: As used in the electronics industry, noise refers to spontaneous and irregular variations in voltages and currents. Noise voltages are characterized by the absence of uniformity in both waveform and frequency. When such noise voltages are reproduced by a speaker, the resulting sound is equally irregular and is thus "noise".

RANDOM NOISE: This noise is more continuous in nature and has a more uniform amplitude (compared to impulse noise). Nearly all noise is of the random type.

SIGNAL-TO-NOISE RATIO: A comparison of the amplitude of the desired signal to the amplitude of the noise voltage present.

STUDENT NOTES

STUDENT NOTES

STUDENT NOTES

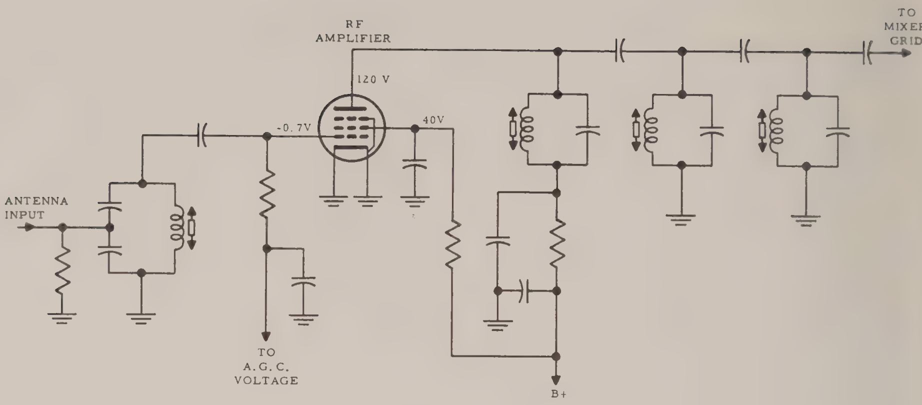


FIGURE 1

RECEIVER RF STAGE

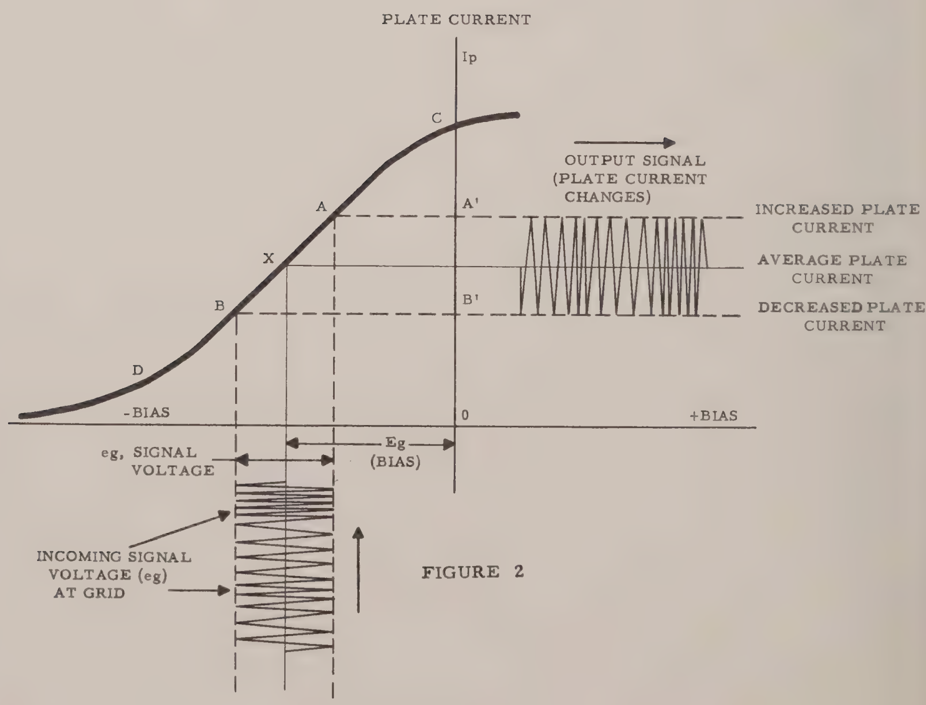


FIGURE 2

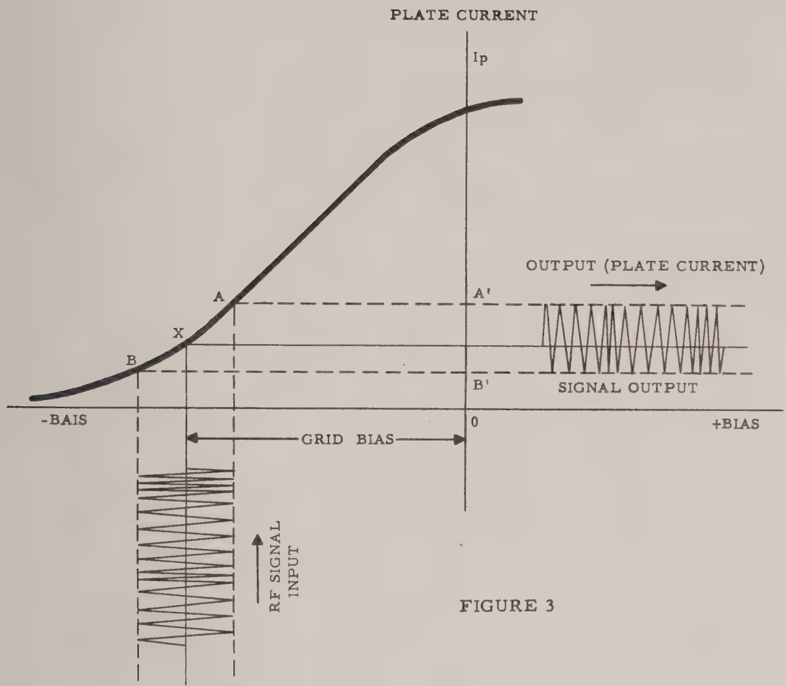
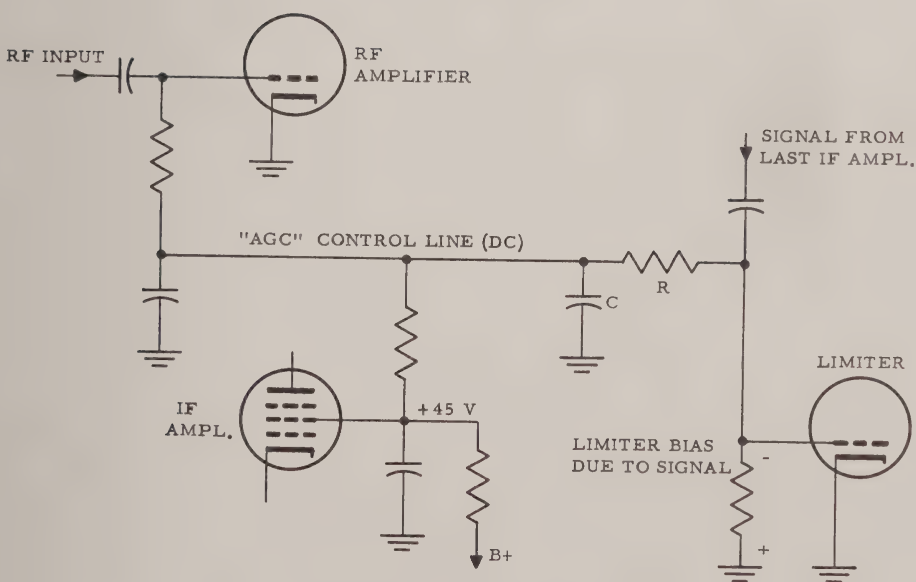


FIGURE 3



DELAYED AGC CIRCUIT
FIGURE 4

Motorola Training Institute

4501 West Augusta Blvd., Chicago 51, Ill.

Please PRINT or use STAMP.

Name ______________________________ Student No. ______

Street ________________ Zone ____ Date ______

City ______________ State ________ Grade ______

Examination, Lesson RA-3

1. What is the purpose of the RF stage in the FM Communications receiver? (Check any and all correct answers.)

   A. To improve the overall signal-to-noise ratio. A. ______
   B. To increase the RF selectivity. B. ______
   C. To override mixer noise. C. ______
   D. To reduce the amount of noise generated in the receiver. D. ______

2. Indicate the order of the following tubes with respect to their internal noise generation, placing the least noisy first.

   Heptode ______ Remote cutoff pentode ______
   Triode ______ Sharp cutoff pentode ______

3. If a strong interfering signal reduces the gain of a receiver, the action is known as ______.

4. A receiver is designed to operate at 141.8 mc. One interfering signal coming into the receiver is 141.52 mc. What additional frequency is needed to cause intermodulation?

   A. 142.14 mc. C. 142.0 mc.
   B. 141.68 mc. D. 141.24 mc. ANS. ______

5. Which of the following may reduce the effects of intermodulation and desensitization?

   A. Change the frequency of the receiver being interfered with. A. ______
   B. Change the frequency of any interfering signals. B. ______
   C. Relocate the antennas of the interfering transmitters. C. ______
   D. Use high-Q cavities parallel to the input of the receiver input, tuning them to the frequency of the interfering signals. D. ______

6. In addition to the impedance transformation taking place in the input circuit of the receiver, between the antenna and the grid of the RF amplifier, the input circuit provides a step up of the signal voltage and improves the signal-to-noise ratio. TRUE ______ FALSE ______

7. In order to provide good selectivity with maximum gain, tuned circuits:

   A. Should be overcoupled. A. ______
   B. Have a high Q. B. ______
   C. Must be critically coupled. C. ______
   D. Must have a low Q. D. ______

8. Indicate the incorrect statement about the Q of a tuned circuit.

   A. Q indicates the ability of a circuit to reject unwanted freq. A. ______
   B. The Q of a circuit increases with an increase of resistance. B. ______
   C. In high-frequency applications, the Q of a circuit is determined mainly by the Q of the coil. C. ______
   D. A high Q provides good selectivity. D. ______

9. Underline the correct words in the following statements.

   The RF amplifier is operated in class A to provide (maximum)(minimum) gain and (maximum)(minimum) distortion. The (pentode)(triode) tube gives more gain, but has (more)(less) noise. It is desirable to have a (low)(medium)(high) signal-to-noise ratio from the RF stage.

10. "Delayed" AGC action in a receiver is used to: (check all correct answers)

    A. Maintain maximum receiver selectivity at all times. A. ______
    B. Keep maximum sensitivity for all signals. B. ______
    C. Prevent the AGC action from taking place for a short time after a strong signal enters the receiver. C. ______
    D. Reduce the RF gain only on strong signals. D. ______
    E. Reduce intermodulation. E. ______
    F. Keep the overall amplification at maximum for weak signals. F. ______

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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-4
FM RECEIVERS

High-Frequency Oscillator, Mixer and IF

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-4
FM RECEIVERS

High-Frequency Oscillator, Mixer and IF

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

THE HIGH FREQUENCY OSCILLATOR - MIXER AND FIRST IF AMPLIFIER

LESSON RA-4

TABLE OF CONTENTS

NOTICE

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Providing "Handie-Talkie" pocket size Two-Way Radio transmitters and receivers for the foot patrolman or officer on the beat has been one of the most significant advances in police radio since mobile radio was first placed in police cars. Now any officer on the force can be constantly in touch with patrol cars or headquarters, for orders, for requests for assistance, for stake-outs and for coordinated searches or enforcement activities.

THE HIGH FREQUENCY OSCILLATOR, MIXER AND FIRST IF AMPLIFIER

Lesson RA-4

Introduction

Figure 1 shows in block form, that portion of a communication receiver usually referred to as the "front end." This includes the RF amplifier, the oscillator-multiplier, the mixer and the first IF amplifiers stages.

The purpose of the front end of a communications receiver is to provide an output signal which (1) has good amplitude with a minimum of noise, (2) is relatively free from all spurious responses such as image frequency and intermodulation, and (3) has a constant center frequency of 12 mc in this example. (The first IF frequency may be different in other model receivers. Figure 1 follows the block diagram discussion of the preceding lesson). To meet these requirements, the RF and IF stages must provide the required amplification with excellent selectivity, and the oscillator must be extremely stable.

Since the RF amplifier was discussed in the preceding lesson, this assignment will be confined to the remaining front-end stages. The oscillator and mixer of figure 1 convert the RF signal to a 12-mc IF. (The oscillator is crystal controlled to maintain the IF at 12 mc). The necessary rejection of unwanted signals is realized by using six highly-efficient tuned circuits at the IF frequency. While the mixer has low gain, the IF amplifier affords the amplification necessary (1) to compensate for the insertion loss in the selective (Permakay) filter following the second mixer and (2) provide some reserve gain for this portion of the receiver. Let us now proceed with a more detailed discussion of these several stages.

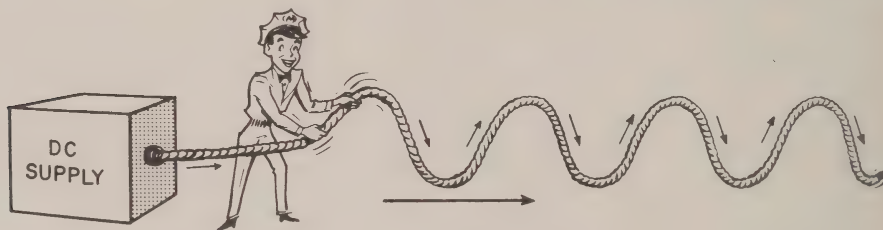
The High-Frequency Oscillator

The basic function of any oscillator is to change DC energy from a power supply into AC energy at a specific frequency. Many types of oscillators have been developed to meet a variety of requirements. The most important of these requirements, insofar as the communications receiver is concerned, is stability. The Colpitts type oscillator, which also can be readily adapted to crystal control, appears to be the most popular in this respect.

Before studying the more complicated crystal-controlled oscillators actually used in communi-

cations receivers let us review the operation of the basic Colpitts circuit. In figure 2 some of the output energy, present in the cathode circuit, is fed to the grid circuit, in order to maintain the oscillating current in the tank circuit (composed of L1, C1 and C2).

compensates for the losses in the grid circuit, thereby maintaining the oscillating current in the tank circuit at a constant level. That is, the RF grid voltage has a constant amplitude from one cycle to the next.



An Oscillator Changes the DC Energy from a Power Supply into AC Energy.

Like most oscillators, the stage is operated in class C. During a small portion of each RF voltage cycle in the tank, the grid is made positive with respect to the cathode, and C3 is charged. During the remainder of the cycle this capacitor must discharge through R1, but because of the high resistance of R1 only a small amount of charge is lost and a relatively high biasing voltage is maintained across C3.

Also, during the positive portion of each RF cycle the grid is unbiased to allow a short pulse of plate current. This pulse of current appears in the cathode coil L2. Tank capacitor C2 receives some energy or charge from the cathode current pulse through coupling capacitor C4; this feedback energy is "in phase" with the circulating tank current and compensates for the losses in the grid circuit, thereby maintaining the oscillating current in the tank circuit at a constant level. That is, the RF grid voltage has a constant amplitude from one cycle to the next.

In order to satisfy the rather stringent frequency control requirements, the modern communications receiver must employ crystal-controlled oscillators. The state of the art has not progressed to the point where it is practical to use a crystal-controlled oscillator at 160 mc, which is the local oscillator frequency required in figure 1. Therefor, a lower frequency oscillator is used, with a frequency multiplier arrangement supplying an output at a harmonic of the basic frequency. In figure 1, the oscillator frequency is 32 mc, and the 5th harmonic (160 mc) is selected and applied to the mixer.

Class C operation is essential for the generation of harmonic energy, particularly where a higher order of harmonic (such as the fifth) is desired. Because of the very short pulse of plate cur-

rent and a distorted grid voltage waveform (the result of grid current), the plate circuit contains a relatively high harmonic content. All that is required now is a highly efficient tuned circuit at the frequency of the desired harmonic. (The output voltage at any harmonic frequency will be directly proportional to the impedance offered to that frequency by the plate tank.)

In figure 3 the oscillating section, composed of the grid and cathode circuits, is the same as in figure 2. Oscillation also takes place in the same manner as in figure 2. Instead of the plate of the tube acting as the anode for the oscillator, however, the screen grid has this function in figure 3. The screen grid does not offer any impedance or opposition to AC, but its positive voltage establishes the required cathode current. Maintaining the anode (screen) at a constant DC voltage improves the frequency stability of the oscillator.

The screen grid voltage of figure 3 is kept constant by the screen-grid bypass capacitor. Furthermore, with the screen at a constant DC potential, the reactance between the plate circuit and the grid circuit is minimum. The only "connection" between these circuits is the common electron stream through the tube. This arrangement is then a form of electron - coupled oscillator. Therefore, any change of impedance in the plate circuit, such as tuning, has a minimum effect upon the oscillator frequency. This contributes greatly toward the ultimate stability of the circuit.

The plate tank is a high-Q circuit, tuned to the desired harmonic. This tank must offer a very high impedance at the chosen harmonic frequency in order to establish a reasonable voltage at the output (mixer). In addition, the impedance of the plate tank must be minimum at all other harmonic frequencies; otherwise, voltages at these frequencies will reach the mixer and may cause spurious response.[1]

Even though the electron-coupled, Colpitts oscillator (figure 3) is relatively stable, it is not satisfactory for communications equipment. The only known practical answer to the required high degree of stability is the crystal controlled oscillator. This is often a modification of the basic circuit just described. Before going ahead, however, it is well that we first take a look at the characteristics and operation of crystals.

Quartz Crystals

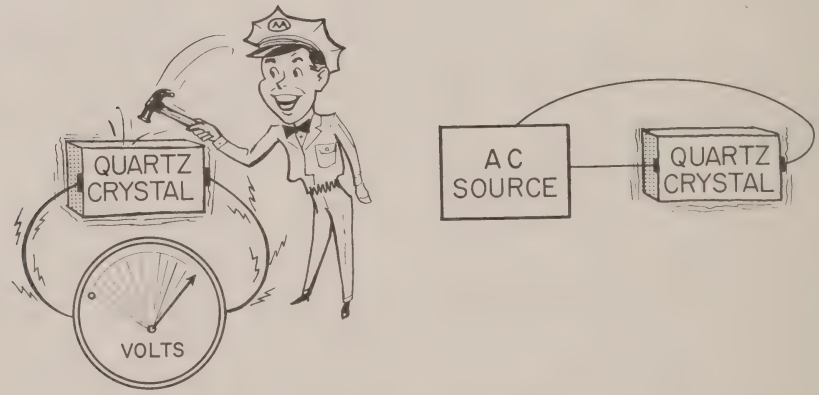
Certain crystalline materials such as quartz, tourmaline and Rochelle Salts have a most interesting property. If one of these substances is distorted mechanically, an electric charge is developed. Conversely, when the crystal is placed in an electric field it will be distorted mechanically. This property is known as the

1. See TM 11-662 Theory and Applications of Electron Tubes, pages 159-162; also TM 11-668 FM Transmitters and Receivers, pages 141-142; also FM Transmission and Reception, by Rider and Uslan, pages 256-262.

Piezoelectric Effect. Of the many substances which exhibit Piezoelectric properties, quartz is the most satisfactory for frequency control purposes. Rochelle Salts has a very intense activity but is too unstable both physically and electrically. Tourmaline is a rare gem material. In addition to being costly, its frequency stability is not comparable to that of quartz.

respect to the axes of the crystals; they must also be free from mechanical and electric flaws.

If a crystal is placed in an oscillating electric field it will vibrate mechanically and produce a voltage across its faces at the frequency of the applied voltage. The magnitude of this voltage is very small unless the frequency



Mechanical Vibration of a Quartz Crystal Produces a Voltage Across that Crystal. In an Oscillator the Crystal is Self Excited by an AC Voltage of the Crystal Resonant Frequency.

While quartz is found in many parts of the world, the most suitable in any quantity comes from Brazil. Quartz is a silica product and is very hard. Besides its use for frequency control in electronic equipment it is used in lenses, balance weights, chemical wares and abrasives. Only crystals of high purity can be used in electronic equipment.

Small "plates" are cut from the raw crystals, and they must be cut in certain directions with

applied corresponds to the natural vibrating period of the plate. At this natural vibrating frequency the voltage developed across the crystal is considerable. In fact, a strong electric field may cause vibrations sufficient to rupture or fracture the crystal.

The electrical action of quartz crystals may be analyzed by referring to figure 5, which shows an equivalent electrical network. The inductance (L) represents the crystal mass, the capacitance (C)

the resilience (elasticity), and the resistance (R) represents the frictional losses. C1 is the shunt capacitance due to the crystal electrodes, with the crystal acting as the dielectric. C2 is the series capacitance between the crystal and its electrodes.

At the frequency where the reactances of C and L are equal, the circuit becomes series resonant. This represents the natural frequency of the crystal. At some slightly higher frequency the combined reactance of C and L will be inductive and numerically equal to the reactance of C1. This is the parallel or antiresonant frequency. C2 is effective only when the crystal electrodes are not in contact with the crystal faces.

The value of the inductance (L) is very large and its reactance is many times greater than the resistance (R). This results in a very high Q. The average for commercial crystals ranges from 6000 to 60,000 and even higher. In an oscillator operating at radio frequencies, the frequency stability is dependent upon the Q of the frequency determining tank or tuned circuit.

The operating frequency of an oscillator is that frequency producing a net zero reactance of all the circuit components. Any circuit changes caused by varying voltages or aging of the tubes necessitates a frequency change to keep the reactance at zero. Because of the high Q and steep resonance curve of a crystal, a minor change of frequency results in a comparatively large change of reactance in order to maintain oscillation. Thus, the change of the crystal oscillator frequency to adjust for circuit variations is extremely small.[2]

The Resonant Crystal

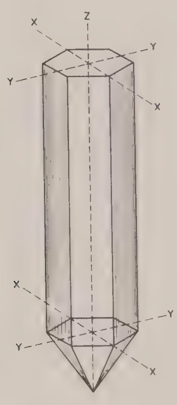
In some oscillator circuits the crystal usually operates as a parallel resonant circuit, and these crystals are calibrated at their parallel resonant frequency. The effective value of capacitance C1 of figure 5 changes when a crystal is placed in a vacuum tube oscillating circuit. C1 will be affected by the dynamic input impedance of the tube and by the capacitance of the leads to the crystal. Because of these factors the operating frequency of a crystal will vary with the circuitry of each oscillator. This suggests the possibility of variable frequency control of the crystal oscillator and becomes most useful in compensating for normal frequency changes which occur in the oscillator.

Warping

All crystals will change in frequency due to a natural "aging" of the crystal. (Recent advancement in crystal techniques, however, have reduced this effect to a very minimum.) There are also minor variations due to circuit changes. Regardless of how or why a fre-

2. See TM 11-662 Theory and Applications of Electron Tubes, page 162

quency change takes place, it is undesirable and may render the receiver inoperative. Assuming the frequency drift is small (and it usually is), it is possible to bring the oscillator back on frequency by varying a small capacitance in series or in parallel with the crystal. This changing of the oscillator frequency by a variable capacitor (or coil) is called "warping".



This Sketch Shows the Three Basic Axes of a Quartz Crystal.

The amount of warping provided in a circuit depends upon the requirements of the receiver and the probable shift of the oscillator frequency at the mixer. If a receiver uses an oscillator-multiplier operating at the fifth harmonic, the change of frequency is five times greater at the mixer than at the oscillator section. As an example, in figure 1 a change of 2 kc at the oscillator frequency produces a 10-kc change in the mixer signal, which, in turn, allows a 10-kc shift in the 12-mc IF.

Quartz Crystal Temperature Coefficient

The natural frequency of a crystal is influenced to an appreciable degree by the temperature at which it is operated. The extent and character of this temperature effect is determined by the manner in which the crystal is cut from the natural quartz, the shape and size of the crystal, the precision in grinding the crystal and the characteristics of the crystal itself. The frequency change is expressed in the number of cycle changes per million cycles of crystal frequency per degree centigrade variation in temperature. This change is in cycles per second and is termed the temperature coefficient of frequency.

A positive coefficient means that the crystal frequency increases with an increase in temperature and a negative coefficient indicates a frequency decrease with a increase of temperature. "Zero" temperature coefficient crystals have a relatively small change of frequency with temperature changes, being positive at some temperatures and negative at others. Thus, for the highest degree of frequency stability in a crystal oscillator, it is necessary to keep the crystal at a constant temperature.

Modes of Crystal Vibration

While some crystal oscillators operate on the fundamental crystal frequency and the crystal acts as

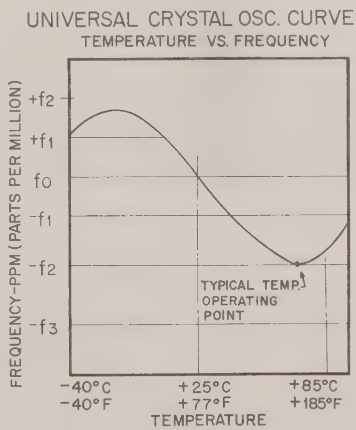
a parallel resonant circuit, there are other arrangements which utilize the series operation of a crystal. One popular oscillator is the series mode type in which the crystal vibrates at approximately the third harmonic of the fundamental frequency.

Figure 6 illustrates vibration of a crystal plate at its fundamental frequency and at the third harmonic frequency. An interesting fact in connection with this series mode of vibration is that the harmonic frequency may be as much as 50 kc away from three times the fundamental oscillating frequency of the plate. This is due to the difference in the manner (or mode) of vibration and is not constant for all crystals.

Newer crystal techniques now allow series mode vibration at the fifth, seventh and other odd harmonics of the fundamental frequency. This means that oscillators which operate at the required local oscillator frequency are possible in the low-frequency band, 24 to 54 mc. This eliminates the need for the multiplier circuit in the receiver oscillator section.

Low temperature coefficient crystals have been developed for all normal frequency ranges. These crystals operate in "shear" (figure 6) and have excellent frequency stability for temperature changes. "Shear" vibration means that the outer faces of the crystal move in opposite direction while the center of the crystal remains relatively constant (on fundamental frequency only). Above 16 or 17 mc, fundamental low-drift plates become quite thin and fragile, but the upper frequency range is extended by using lower frequency crystal plates and grinding them so that they will oscillate at their third or fifth harmonic. For this type of operation the crystal must be used in a circuit designed for series-mode operation.

To meet the rigid requirements of modern communications practice, crystal oscillators using temperature-controlled heating ovens may have an accuracy of .0005 percent. Comparing this with time, a clock having the same accuracy will vary about one minute



This Curve Shows the Change of Crystal Oscillator Frequency with Changes of Temperature. A Constant Operating Temperature is Maintained by a Thermostatically Controlled Oven.

in three or four months. Compared with distance, this is an accuracy to within one inch in every two miles. To insure positive operation in "split channel" applications, practical oscillators of even greater stability have been developed.

Aging in Crystals

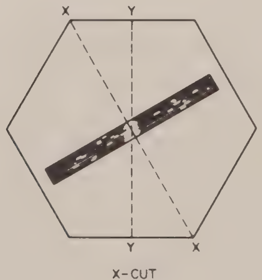
We previously spoke of the aging of a crystal. This refers to a natural change of frequency that takes place over a period of time. All crystals age to some degree, and this usually occurs during the first few months the crystal is used. After the initial aging period, crystals are likely to maintain a stable frequency for the rest of their natural useful life. Aging in crystals may be accompanied by a deterioration in activity. If crystal activity drops as much as 25 percent during the initial aging period it is possible that the crystal has some contamination of natural flaw.

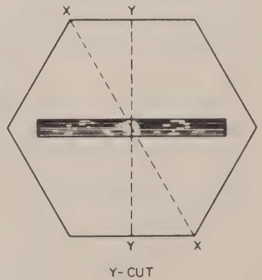
Contamination results when foreign matter accumulates on the crystal. This may seriously affect the crystal's operation as to both frequency and activity. Because modern crystals are "plated," there is no practical field repair suggested, and such crystals should be returned to the factory for service.

Grown (Synthetic) Crystals

Synthetic quartz crystals are now available, but because of their high cost they are still in the research and development stage. These crystals are not synthetic in that they are a substitute material, but they have been produced by controlled methods--or "grown." Physically, they resemble the natural quartz and may prove to be superior in that they are relatively free from impurities.

Another advantage is that grown quartz can be supplied in large slabs of the proper "cuts,"





Crystal Oscillator "Plates" are Cut from the Crystal According to the Crystal Axes.

so there is comparatively little waste. (For natural quartz, a very high percentage of the original material is waste. Only that part of the crystal which is free from impurities, and of the proper cut, can be used.) Indications are that synthetic quartz may eventually replace the natural quartz crystal.

The Crystal Controlled Oscillator

Figure 4 shows the basic circuit of the crystal controlled oscillator. The main difference between this circuit and that of figure 3 is the crystal inserted in the feedback path between the cathode and the two tank capacitors. (The coupling capacitor, C4 is variable for warping purposes.) This circuit uses a series-mode crystal, designed to operate at the third harmonic frequency. The grid tank circuit is tuned to the crystal frequency. The crystal acts like a series circuit; at resonance, it offers a very low impedance to the feedback current from the cathode to the tank, and the circuit operates in much the same manner as figures 2 and 3. At any frequency other than resonance the impedance of the crystal rises sharply and the feedback current is too low to sustain oscillation. Thus, the circuit can oscillate only at the resonant frequency of the crystal.[3]

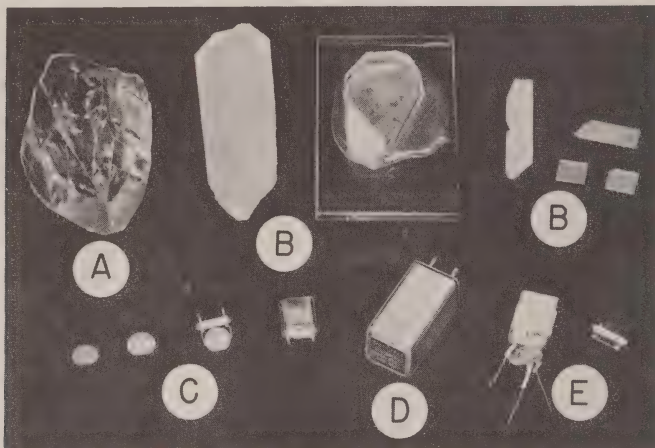
For Reliable Receiver Operation the Local Oscillator Must Generate a Constant-Frequency RF Signal.

Metering The Crystal Oscillator

The operation of the circuit of figure 4 depends largely upon the crystal action, and its stability is such that tuning the grid tank circuit does not noticeably affect the frequency. The tank circuit, which now controls the amount of oscillator activity, is normally adjusted for maximum oscillator output. This is made possible by measuring grid current. As the tank is adjusted to the crystal frequency, the voltage across the tank increases and causes a high grid voltage.

Grid voltage or current may be recorded by an arrangement shown in figure 7. A sensitive microammeter (such as a 50 ua movement), in series with a suitable resistor is connected between the oscillator grid and ground. As the tank is adjusted to resonance, the meter reads maximum. In figure 7, the bypass capacitor and resistor are mounted close to the oscillator tube socket. The capacitor removes all RF from the meter lead.

3. See TM 11-668 FM Transmitters and Receivers, pages 142-146.



Construction of a Modern Temperature Controlled Crystal. A. A Raw Quartz Crystal. B. Steps in Cutting Plates. C. Crystal is Plated and Placed in a Holder. D. The Final Assembly. E. The Thermostat and Heater Assembly

All crystal oscillators do not behave alike when being tuned through resonance, and this must be kept in mind by the serviceman when making adjustments. For example, while the meter reading may be maximum at resonance, the grid activity may exhibit a marked lack of uniformity at each side of resonance. On one side of resonance, the grid activity shows a gradual decrease; on the other side of resonance, the oscillator stops working, and the meter reading drops to zero!

When tuning such oscillators, this condition must be taken into account. If the circuit is adjusted to maximum on the meter, there is a high probability that some change in the operation will suddenly shift the frequency and oscillation will stop. For this particular type of oscillator, the tank should be adjusted not to maximum, but to a frequency slightly to the side of resonance where the activity decreases gradually. Then, should the frequency change in either direction, the oscillator will continue to operate. (Before adjusting any oscillator, it is essential that the serviceman first read the instructions in the service manual.)

**Motorola
Oscillator-Multiplier Circuit**

Figure 8 shows the final arrangement of a high frequency oscillator and multiplier stage as incorporated in many Motorola receivers. It contains several minor modifications of the basic

oscillator circuit of figure 4, but the principle of operation remains essentially the same.

At 32mc, the capacitance of the crystal acts like a partial short for the RF. Coil L4, parallel to the crystal, tunes this capacitance to resonance, effectively removing the "short." The resistor across L_1 improves the stability of the parallel-tuned circuit. Coil L3 permits efficient oscillator operation over a wide range of frequencies, thus providing for any desired change of channel frequency. Warping capacitor C4 aids in setting the oscillator on the exact frequency, compensating for any crystal aging or circuit changes. Although C3 is located in a different part of the circuit, it is still the grid capacitor and serves the same purpose as C3 in figure 3.

The two tuned plate circuits operate at the fifth harmonic (160 mc) of the crystal frequency (32 mc). These high-Q circuits are critically coupled for maximum rejection of all other harmonics. The signal fed to the mixer is taken from a low impedance tap on the second tuned circuit; in this way, only the correct harmonic reaches the mixer with appreciable amplitude.

In addition to the voltage dropping resistor and bypass capacitor at the screen grid, a second resistor is connected between the screen grid and ground. This resistor maintains a more constant voltage at the screen for changes of screen current and supply voltages, thus improving the overall stability of the circuit.

The design of the oscillator of figure 8 is such that it is stable over the entire tuning range of the tank circuit and it is thus possible to tune the grid circuit for maximum activity as well as output.

In order to have maximum signal from the mixer, both oscillator plate tank circuits must be tuned to 160 mc. Within the design limits of the mixer, the amplitude of the 12-mc If output voltage increases in direct proportion with the strength of the 160-mc voltage. Thus, by monitoring the signal strength at a later stage (limiter), the plate tanks of the oscillator may be adjusted for a maximum reading.

The tuning range of the oscillator plate circuits is designed so that these circuits cannot be tuned to any harmonic frequency other than the fifth harmonic. This prevents mistuning them to an incorrect frequency, resulting in a false indication in the following circuits of the receiver.

Constant Temperature Ovens

All crystals exhibit some change in frequency with any change in temperature. The normal drift may remain within the requirements of receiver operation for low-frequency receivers; but at higher frequencies, where

the amount of frequency change is multiplied by a factor depending upon the oscillator harmonic chosen, a constant-temperature oven becomes essential.

The temperature within these ovens is higher than the operating temperature of the equipment. A heating element (operated from the car battery in mobile applications) is turned on and off by means of a thermostat, thus maintaining an even temperature at all times. By maintaining the crystal at a constant temperature, the oscillator does not drift as a result of changes in ambient temperatures.

The heating element, thermostat, and crystal are usually built into a small plug-in assembly. Although not shown on the schematic of figure 8, the 32-mc crystal is part of a constant-temperature oven assembly.

The High-Frequency Mixer

The incoming RF signal and the oscillator RF voltage combine in the mixer stage to create the desired intermediate frequency. For best results the oscillator voltage should be many times greater than the RF input. (In most receivers the oscillator will generate more than 1/2 volt). When the RF signal is small as compared to the oscillator voltage, and when the oscillator voltage is applied to the mixer at a point of low impedance (such as the cathode), the possibility of spurious response and intermodulation is minimized.

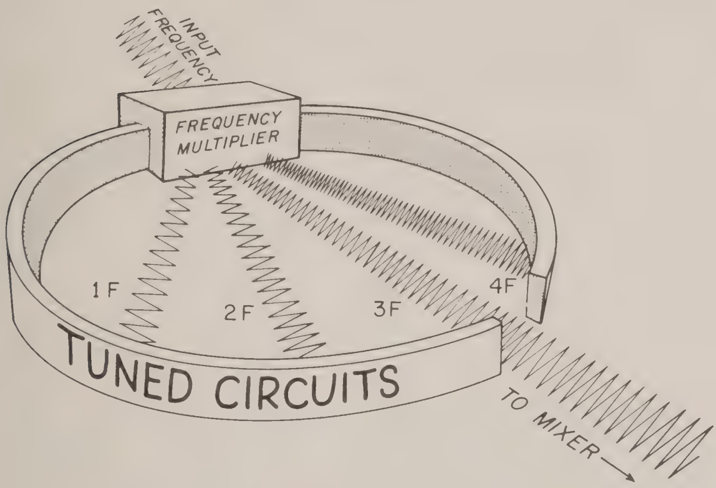
The conversion transconductance, or amount of gain possible in a mixer stage, is about one-fourth the gain which would be possible if the same tube were operated as an amplifier. Since the mixer output voltage depends largely upon the impedance presented to the IF signal current in the plate circuit, it is desirable that this plate circuit be highly selective.

A typical mixer, with an input of 172 mc is shown in figure 9. The local oscillator voltage at 160 mc is injected into the cathode circuit. The 1.25-volt bias developed across the cathode resistor operates the tube at the lower portion of the characteristic curve. A triode is used in the mixer stage so that the noise generation will be low, and the three high-Q, critically-coupled tuned circuits in the plate provide maximum IF signal output with good selectivity. (More will be said about Q and coupling in the following lesson.)[4]

Does Heterodyning Affect Deviation?

The question of deviation always arises in connection with mixer action and the resulting IF signal. We can best explain this by giving an example. Assume the incoming 172-mc signal has a deviation of ± 15 kc.

4. See TM 11-668 FM Transmitters and Receivers, pages 127-140; also FM Transmission and Reception, by Rider and Uslan, pages 256-262.



The Frequency Multiplier Generates Many Harmonic Frequencies. Only the Desired Harmonic (3F in this Illustration) is Selected and Applied to the High-Frequency Mixer.

This means the RF swings 15 kc above and 15 kc below center frequency. The incoming RF is not a constant frequency of 172 mc, but varies between 171.985 mc and 172.015 mc.

When the RF is at center, or 172 mc, it combines with the constant 160-mc oscillator voltage to produce the center IF frequency of 12 mc. When the RF is 171.985 mc it again combines with the 160-mc signal, but the difference is now 11.985 mc. Similarly, when the RF is 172.015 mc, the difference frequency is 12.015 mc. The IF frequency thus varies between 11.985 and 12.015 mc, which is a deviation of ± 15 kc. From this we may generalize that heterodyne action does not change the deviation; the resulting IF has the same deviation as the applied RF.

The First IF Amplifier

The first (12 mc) IF amplifier, which is located between the first and second mixers, is shown in figure 9.

A high-gain pentode is used for the circuit of figure 9, and the tube is operated with relatively low voltages at the plate and screen. Bias is developed by means of a cathode resistor and bypass capacitor.

Besides amplification, the seemingly endless problem of

selectivity must also be taken into consideration, for in present day operation, a receiver cannot have too much selectivity in order to be free from intermodulation and other spurious response.

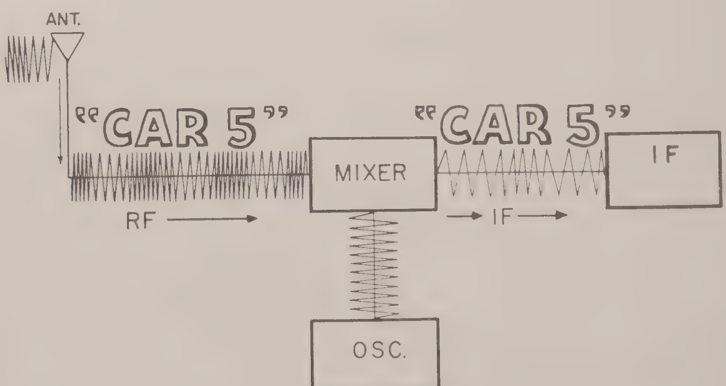
Even with good selectivity in the first IF section, it is possible to have intermodulation and image-frequency response in the second mixer as well as in the first mixer. The last IF frequency is usually 455 kc; the image frequency in the second mixer will therefore be spaced 910 kc from the channel frequency of 12 mc. With the oscillator operating above the IF, any signal reaching the second mixer which is 910 kc above the 12-mc IF will produce an image response.

Selectivity is obtained by means of the tuned circuits of the first IF amplifier. Three high-Q, critically-coupled circuits are employed in both the plate and grid for the purpose of offering high impedance to the IF frequency, providing gain and selectivity.

Summary

This lesson has been largely restricted to a consideration of the 172-mc receiver, and since there is considerable difference in the front end of the 450-470 mc receiver, the latter calls for further study. Before proceeding to study the 450-470 mc receiver however, let us first review what has been said in this lesson about the operation of the high-frequency oscillator-mixer and first IF amplifier.

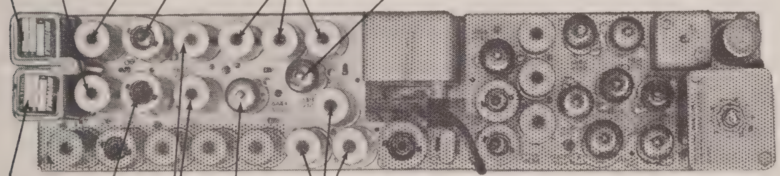
1. The purpose of this portion of the receiver--the front end--is to deliver an interference-free signal with a high s/n ratio to the second mixer.



Heterodyning Does Not Alter the Deviations of the FM Wave; the IF Has the Same Deviations as the Incoming RF.

2. The high-frequency, crystal-controlled oscillator is temperature compensated for maximum stability.

3. The crystal oscillator frequency can be altered (or "warped") to compensate for the natural aging of the crystal. This is usually accomplished by means of a small variable capacitor.



This Photo Shows the Location of the High-Frequency Oscillator-Mixer and First IF Amplifier of a Typical Motorola Receiver.

4. The mixer heterodynes the RF and oscillator signals to provide the required IF. High-Q and critically-coupled circuits in the mixer and IF amplifier plate circuits provide the required selectivity. The mixer is designed for maximum output at the intermediate frequency.

5. The heterodyning process in the mixer does not change the deviation characteristics of the signal. The frequency variations of the IF signal are identical to those of the incoming RF signal.

6. The IF-amplifier provides high gain and sharp selectivity.

The 450.470 MC Receiver

Figure 10 shows a typical 450-470 mc mobile receiver, in block diagram form. Compare this with figure 1, which shows the front end of a communications receiver operating at 172 mc.

There is considerable difference in the design of the front-ends of the two receivers. This is due to the different operating characteristics of tubes and circuits at the higher frequencies.

Because it is difficult to obtain amplification at 450 mc with ordinary tubes, the RF amplifier and mixer tubes are omitted. Instead, the RF section consists of four or five highly selective

tuned circuits which form a "preselector," to reject unwanted signals and to pass the desired channel frequencies with very little attenuation. The preselector presents very little opposition to the passage of the desired signals and it does not add to the noise level. (These tuned circuits are basically a series of tuned "flat" lines. While very practical at these higher frequencies, the larger size of a similar type preselector at lower frequencies would present a mechanical problem).

The RF signal and the oscillator-multiplier output are injected into a crystal mixer to produce the desired IF. While the crystal mixer does not amplify, its noise level is low and the IF output has a satisfactory signal-to-noise ratio. The first actual amplification is provided by the IF amplifier. It is important that this stage produces a signal having a high s/n ratio, in order to result in a noise-free output at the speaker. The cascode amplifier is often used in the first IF stage because of its amplification capabilities and its low noise level.

The cascode amplifier is really two stages of triode amplification, consisting of a neutralized amplifier followed by a grounded grid amplifier. A typical circuit is given in figure 11. Coil L1 allows some out-of-phase energy from the output to feed back to the grid, thus opposing or canceling the effect of the regenerative voltage at the grid due to interelectrode capacitance.

The output of the first triode is applied to the cathode circuit of the second triode (the grid of which is grounded). This second triode requires no neutralization because the feedback voltage due to tube capacitance is degenerative (with cathode injection) and cannot produce instability or oscillation. While the cascode amplifier is actually two tubes operating in series, it is common to refer to the arrangement as a single stage. (In most applications a single twin-triode type tube is used.) The amplification of the cascode amplifier is higher than that of a single pentode, particularly at higher frequencies, and the noise level is lower.

Referring again to figure 10, it will be seen that triple conversion is used in this 450 mc receiver. At the first mixer the 12th harmonic of the oscillator is required. This harmonic is provided by a series of harmonic amplifier stages. For the second mixer the second harmonic of the same oscillator is selected. This second IF frequency varies with the channel assignment. The high-frequency oscillator is crystal controlled and is maintained near its correct frequency by an AFC circuit. The third oscillator frequency is selected so that the last IF will be 455 kc. From here on the rest of the receiver is similar in circuitry to lower frequency receivers.

Propagation characteristics of the 450-470 mc band have been found, in general, to be very satisfactory. In metropolitan areas, multiple reflections between buildings, together with use of a high antenna at the base station, have provided reliable coverage which might not have been possible at lower frequencies. Thus, 450-mc equipment has made two-way communication possible for many services where it otherwise would have been impossible.

IMPORTANT WORDS USED IN THIS LESSON

AGING: As applied to quartz crystals used in oscillator frequency control, aging is a natural change in the crystal frequency evidenced over a period of time.

CRYSTAL-CONTROLLED OSCILLATOR: An oscillator which makes use of a quartz crystal to provide a high degree of frequency stability.

FREQUENCY MULTIPLIER: A form of amplifier which produces an output at some harmonic frequency of the input signal.

HARMONIC FREQUENCY: A frequency which is a whole number multiple of the fundamental frequency.

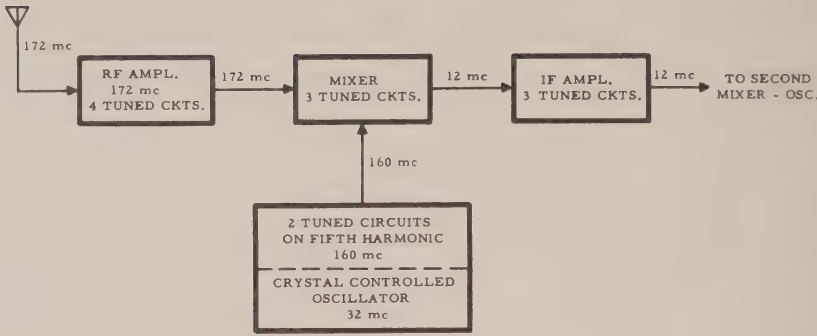
PIEZOELECTRIC EFFECT: A natural phenomenon associated with certain crystals. When a voltage is applied across its faces, the crystal is distorted mechanically. Conversely, when the crystal is subjected to a mechanical strain, a voltage is produced across its faces.

QUARTZ CRYSTAL: A silica material which exhibits Piezoelectric properties. Its most important use in the electronics industry is in conjunction with an oscillator as a frequency controlling device.

WARPING: This is the changing of the frequency of a crystal-controlled oscillator so that it operates exactly at the required frequency.

STUDENT NOTES

STUDENT NOTES



"FRONT END" OF COMMUNICATIONS RECEIVER

FIGURE 1

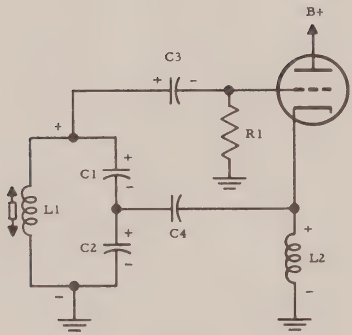


FIGURE 2
COLPITT OSCILLATOR

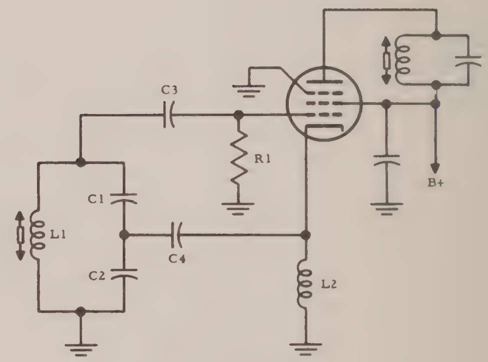


FIGURE 3
OSCILLATOR - MULTIPLIER

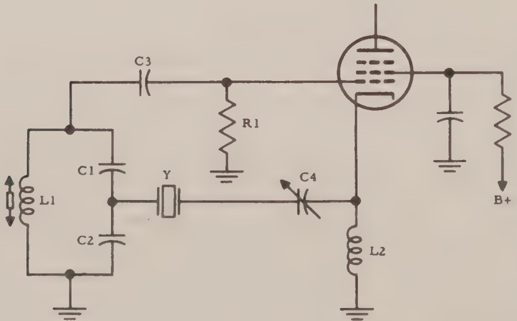


FIGURE 4
CRYSTAL CONTROLLED
OSCILLATOR

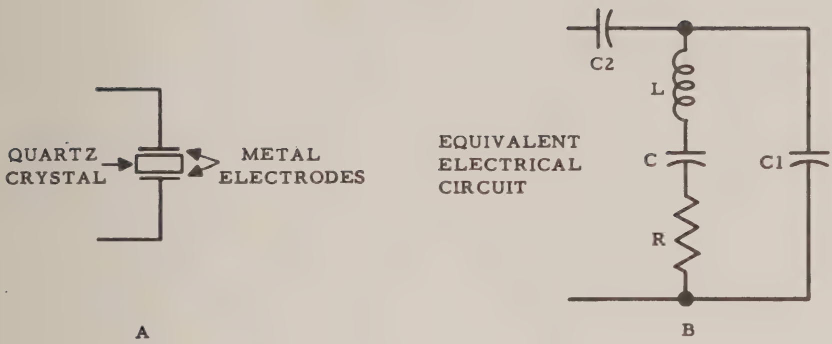


FIGURE 5

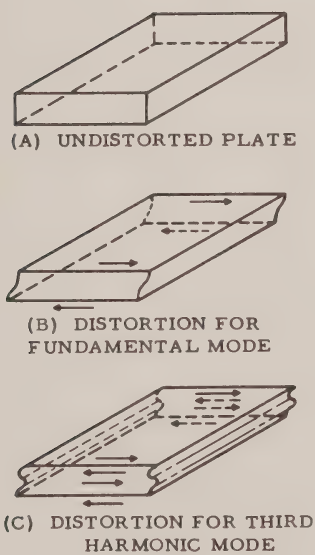
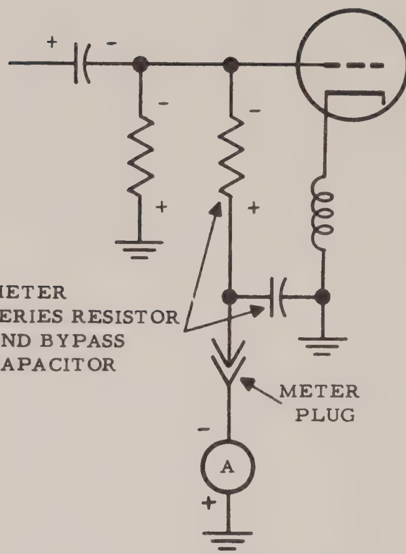
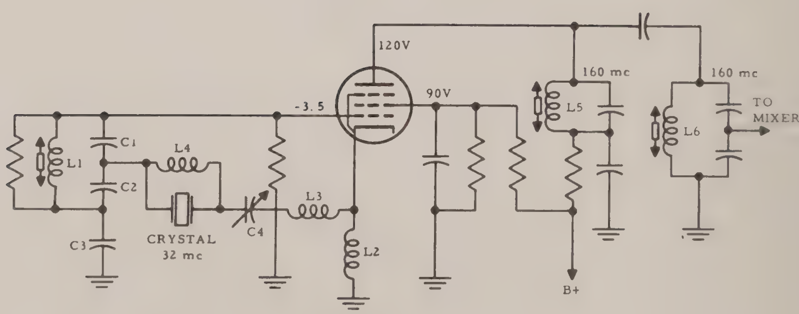


FIGURE 6



OSCILLATOR METERING

FIGURE 7



HIGH FREQUENCY OSCILLATOR AND MULTIPLIER

FIGURE 8

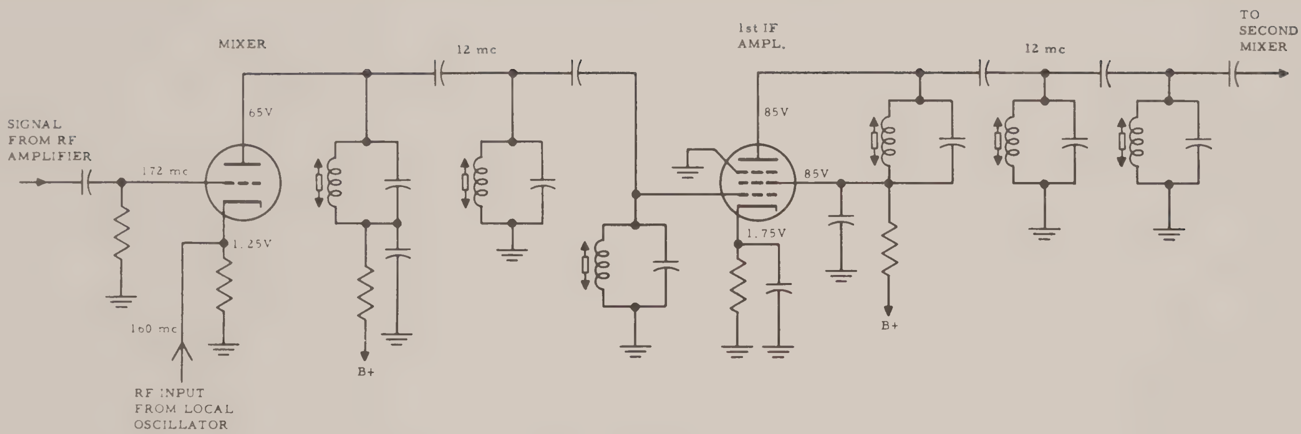
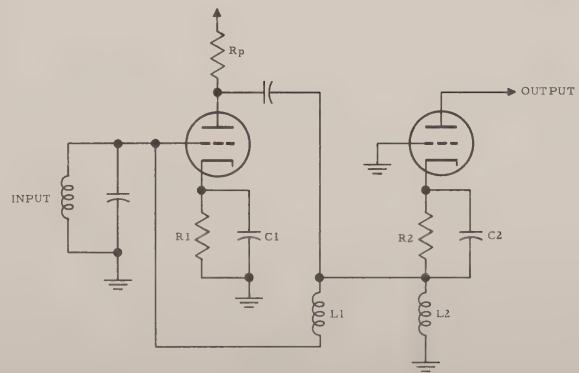
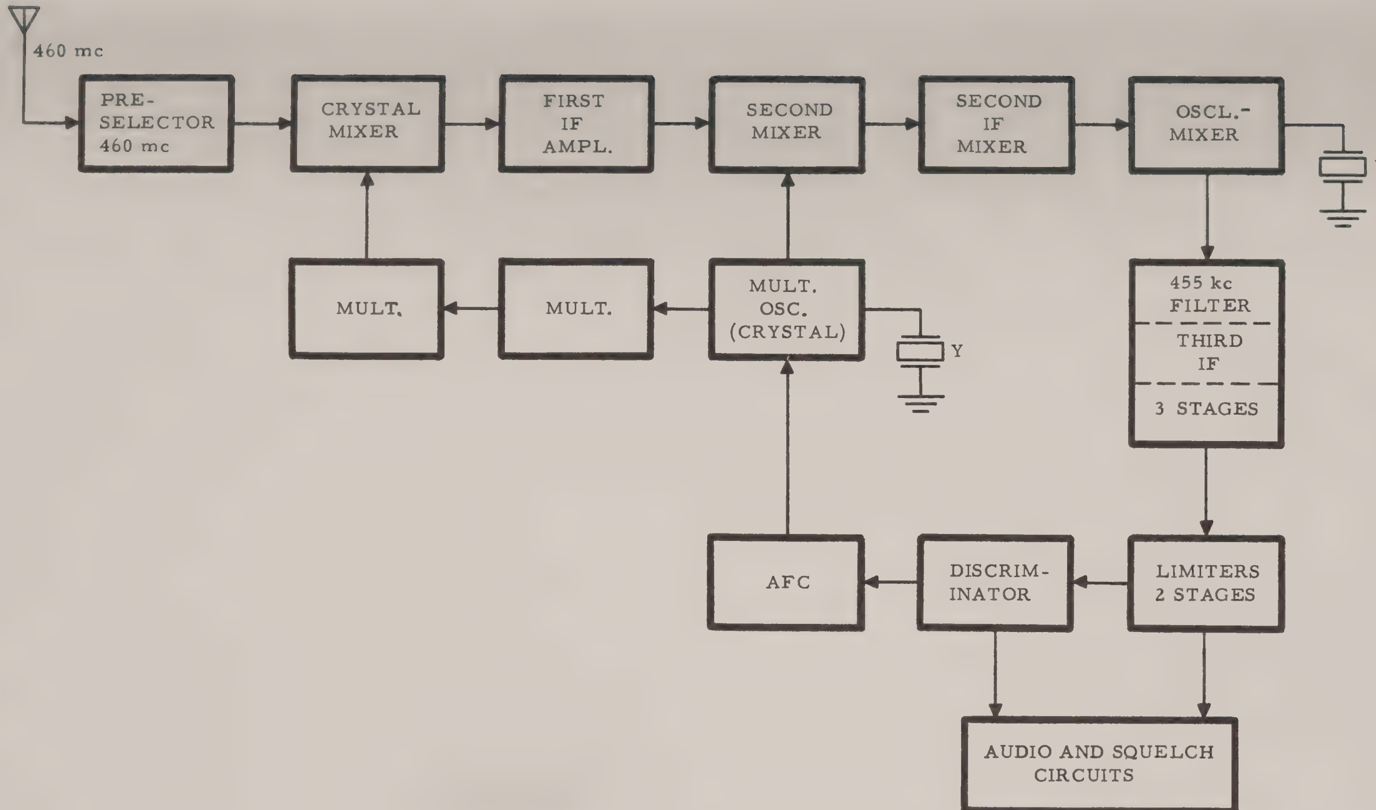


FIGURE 9
MIXER AND FIRST IF AMPLIFIER



CASCODE AMPLIFIER
FIGURE 11



450-470 MC RECEIVER

FIGURE 10

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Street ________________ Zone ____ Date _______

City ______________ State ________ Grade ______

EXAMINATION LESSON RA-4

1. Assuming that the injection voltage from the oscillator to the mixer in figure A has a lower frequency than the RF, the crystal frequency will be ______________________ mc.

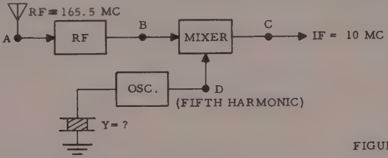

FIGURE A

2. For the values of figure A and Question 1, the image frequency is ______________ mc.

3. Referring to figure A, what is the resonant frequency of the tuned circuits at the following points? A ____ mc; B ____ mc; C ____ mc; D ____ mc.

4. The main advantage of using a crystal-controlled oscillator is ______________________.

5. Which of the following are likely to cause a change in the operating frequency of a crystal controlled oscillator in the two-way communications receiver?

   A. A strong RF signal into the antenna. — A. ________
   B. A weak RF signal at the antenna. — B. ________
   C. A change in crystal temperature. — C. ________
   D. A large change in the oscillator screen grid voltage. — D. ________

6. In an oscillator circuit such as that of figure 8 of this lesson, the crystal acts like a (series)(parallel) resonant circuit. At resonance the crystal presents a (high)(low) impedance and allows (maximum)(minimum) feedback current.

7. The voltage applied from the oscillator to the mixer should be (larger)(smaller) than the incoming RF signal. This improves the receiver's (freedom from intermodulation)(selectivity).

8. The tuned circuits in the front end of the receiver must have good selectivity and minimum insertion loss. This is accomplished by having (high Q)(low Q) circuits with (loose)(tight)(critical) coupling.

9. The incoming signal to a receiver has a frequency of 166 mc and a deviation of 10 kc. This signal is converted to an IF of 11.5 mc. The IF signal will then have a deviation of ____________ kc.

10. The first IF amplifier section of a communications receiver has two main functions. These functions are ______________ and ______________.

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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-5
FM RECEIVERS

Second Oscillator, Mixer and IF Section

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-5
FM RECEIVERS

Second Oscillator, Mixer and IF Section

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

THE SECOND MIXER, OSCILLATOR AND "IF" STAGES

LESSON RA-5

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Since 1945, taxicab operators have been providing faster, more reliable, yet more economical service through radio dispatching. Today about two thirds of the nation's cabs are radio equipped.

THE SECOND MIXER, OSCILLATOR AND "IF" STAGES

Lesson RA-5

Introduction – Review

We are now prepared to discuss the second mixer, oscillator and last IF stages of the receiver, but before proceeding, let us review what has already been accomplished with the signal in the front-end stages.

The RF stage, we found, amplifies the incoming signal and provides considerable RF selectivity, so that the signal at the mixer input has a good signal-to-noise ratio and is relatively free from interfering signals--signals which might cause image response, intermodulation and desensitization.

The high-frequency oscillator is both crystal controlled and temperature compensated, for maximum stability. In order to minimize spurious responses, highly selective tuned circuits at the oscillator-multiplier provide high attenuation of other harmonics, and only the desired harmonic frequency of the oscillator reaches the mixer. The overall effect is that the signal from the mixer has a constant center frequency, is relatively free from interfering signals, and has a good signal-to-noise ratio. The high-frequency IF amplifier stage provides the gain necessary to supply a satisfactory signal to the second mixer. At the same time, the excellent selectivity of the tuned circuits further rejects unwanted signals.

This is what has already been accomplished, in the front end of the receiver. The following remains to be done in the rest of the receiver.

1. Reject all remaining signals except those of the desired channel.

2. Provide a large amount of amplification ahead of the limiters.

3. Remove all amplitude variations (noise voltages).

4. Convert the FM deviations into corresponding audio voltages.

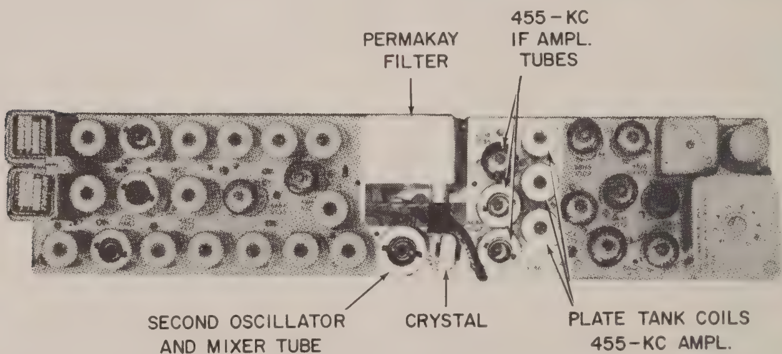
5. Amplify the audio signal in order to operate the speaker.

6. Squelch the noise between transmissions.

In this lesson we shall be concerned with the first two of these functions. (The last four, accomplished in subsequent stage of the receiver, will be discussed in later lessons). In discussing the selectivity of the final IF section of the receiver, we shall make use of selectivity curves. Also, since the amount of rejection or attenuation of unwanted signals is usually rated in decibels, this lesson will include a brief discussion of decibels. With the above preview in mind, let us begin our study of this assignment with the low-frequency oscillator.

Figure 1 shows a typical circuit. With an IF of 12 mc, in order to secure a 455-kc, second IF, the oscillator must be either 455 kc above or 455 kc below 12 mc. As shown in figure 1, the oscillator frequency at 12.455 mc is above the incoming signal.

To insure maximum stability, the second or low frequency oscillator is crystal controlled. Because of its comparatively low frequency, the slight frequency change that occurs in this crystal controlled oscillator due to temperature has no appreciable effect on the operation of the receiver. Thus, the oscillator design is less critical and less complicated, and it is not necessary to use a constant temperature oven. The crystal acts like a parallel-tuned tank circuit controlling the frequency of operation. Feedback is obtained by connecting the cathode to the junction of the two capacitors connected in parallel to the cry-



This Photo of a Motorola Receiver Shows the Location of the Second Oscillator-Mixer, Permakay Filter and Low-Frequency IF Amplifiers.

The Low-Frequency Oscillator

In order to provide for the required selectivity and amplification, the high-frequency IF signal (we have assumed 12 mc in the past lessons) must be converted to a low-frequency IF-455 kc in most communications receivers. This requires another mixer-oscillator combination.

stal. The oscillator voltage is injected into the mixer grid through capacitor C1. The oscillator plate is bypassed to ground and has no active part in the oscillation of the circuit.

The Second Mixer

Two distinct inputs, the 12mc IF signal and the 12.455-mc oscillator voltage, are applied to the second mixer. The heterodyning action, or "beating", of these two inputs produces a difference frequency of 455 kc at the output of the second mixer. While the second mixer stage is operated in class A to minimize the generation of undesired signals, there is a satisfactory output at the second IF frequency. To provide a large voltage at 455kc, the plate load of the second mixer must present a high impedance at this frequency. At the same time, it must act as a low impedance to all undesired signals.

Obtaining Selectivity

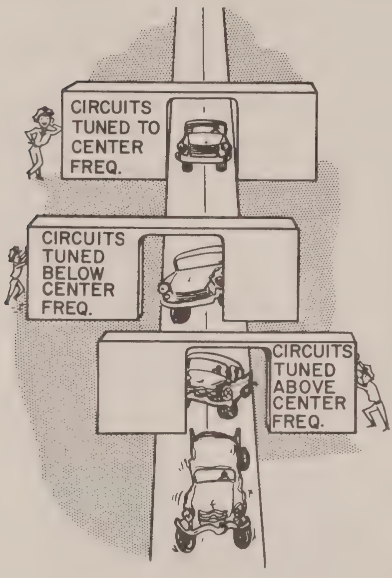
When we remember that all the "intelligence" we want to hear is contained in the sidebands rather than in the carrier, we can appreciate the statement that the bandwidth of the last IF section must accommodate all of the incoming energy. Also, since FM deviations extend a considerable distance each side of center frequency, a frequency response which is both broad and flat is essential. Beyond this "flat top" response, however, a sharp attenuation is required in order to eliminate adjacent channel signals. The theoretical ideal response would be nearly rectangular. In practice, however, a slight curve at the shoulder of the flat top is desirable in order to prevent phase distortion. Ideal selectivity curves, both theoretical and practical, are shown in figure 2.

Transformer Coupling

A conventional transformer-coupled, three-stage IF amplifier section is shown in figure 3. The gain of the circuit depends mainly on the transformer design; also, the selectivity depends on the Q of the tuned circuits and the coupling between the windings.

Figure 4 shows three response curves which are possible with various degrees of coupling between the windings of transformers. Curve 1 illustrates less-than-critical coupling. With all transformer windings loosely coupled the selectivity is very good but the response curve is too narrow to pass all the deviation components. This is undesirable, as FM reception relies on passing all of the "side bands" or deviations. Curve 2 of figure 4 indicates critical coupling; this response curve is similar to curve 1 but the gain is greater. This, too, is undesirable for FM reception. In order to secure a wider response, the degree of coupling is further increased, as shown in

curve 3, but the "dip" in the center of the curve indicates over-coupling-producing uneven amplitude response and phase distortion.[1]



Circuits Tuned Above and Below Center Frequency Distort the Incoming Signal.

By employing overcoupled transformers in certain stages and critical coupling in others, it is possible to obtain a response curve that is relatively "flat" to accept the desired channel signals, and has fairly steep sides for the rejection of unwanted signals. There is considerable interaction between the windings, however, and the alignment of such tuned circuits thus presents a major problem. It is very difficult to secure the proper band-pass response curve, and the complicated tuning procedure which must be employed involves the use of special equipment.

The desired band-pass curve can also be obtained by using critical coupling between stages and detuning successive stages alternatively above and below the center frequency, so that each stage contributes to the over-all bandpass curve. Again the response curve is good, but this procedure results in undesirable phase distortion and the alignment is difficult.

Where the utmost rejection of adjacent channel signals is required, as in the case of the communications receiver, neither of the foregoing arrangements is a completely satisfactory solution. One alternate arrangement involves the use of a "triple tuned" transformer--a transformer equipped with a third, or tertiary, winding. (Actually, a number of these transformers must be used in order to obtain the proper curve with good rejection characteristics).

Such a transformer is shown in figure 5. The primary and secondary are inductively coupled, but the third tuned circuit is capacitively coupled to the secondary. These circuits can be designed for good response characteristics. Again, however, the problem of alignment is a distinct disadvantage and it is necessary to look elsewhere for the ideal solution to the problem of controlled selectivity.

[1]See TM 11-668 FM Transmitters and Receivers, pages 149-152; also FM Transmission and Reception, by Rider and Uslan, pages 263-272.

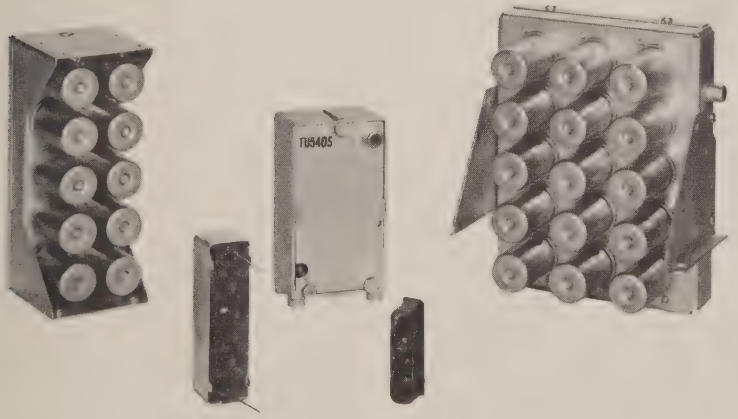
A system which separates the selectivity and amplification functions within the low-frequency IF section has proved to be most successful. This system makes it possible to use a specially designed filter, having the desired band-pass characteristics. Maximum amplification can then be designed into the following IF stages without considering problems of frequency discrimination and phase shift. The block diagram of figure 6 shows the general arrangement.

Immediately following the mixer, the signal encounters a highly selective filter which allows the signal components of the desired channel to pass on to the last IF amplifier strip with comparatively little attenuation. The response curve of the filter is very nearly that of the ideal response shown in figure 2. In operation, the slightly rounded corners and nearly vertical sides of the filter response are most desirable. The signals of the adjacent and other nearby channels are highly attenuated in the filter and do not reach the next stages. The high-gain, three-stage amplifier following the filter is designed for maximum gain and stability. No consideration need be given to selectivity--the only signal present is the desired signal.

Because it plays such an important role in the Motorola receiver, let's inspect this filter in greater detail.

The Permakay Filter

Motorola's answer to the high degree of selectivity required in the modern communications receiver is the very efficient and selective filter which is known under the registered trade mark of "Permakay". While it is pos-

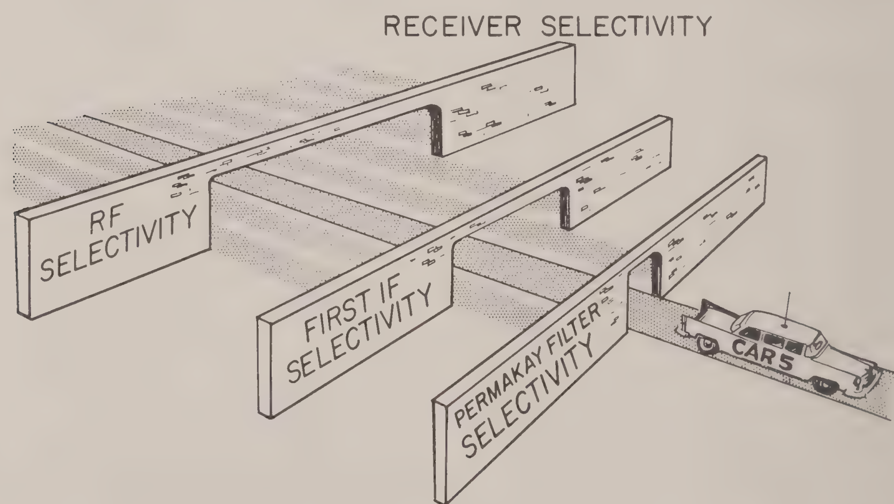


Permakay Filters are Made in Many Sizes. The Very Small Ones are Used in Light, Compact, Portable Equipment.

sible to achieve considerable selectivity by using a great number of individual tuned circuits or simple filters, the resulting loss at the center frequency is prohibitive. Thus, a composite filter with many highly efficient tuned circuits (sections) is necessary. The Permakay filter components are specially designed and arranged so that attenuation of the signal frequency is kept at a minimum. During its manufacture, each completed filter is carefully aligned and tested, and then encased in a highly durable plastic which seals it from all humidity. Because of their rigid construction and the plastic seal, the tuned circuits cannot be jarred out of alignment. Thus, the filter operation remains the same for all conditions and produces positive performance at all times.

Sealing the filter also makes it impossible for anyone to tamper with the tuning adjustments and upset the band-pass characteristics.

The Permakay filter has been so successful that its operation is guaranteed for life of the equipment. Also, by "packaging" the filter it is very easy to change the unit should the receiver selectivity requirements change. That is, when new station allocations on the adjacent channels make it necessary to employ a greater degree of selectivity, all that need be done is to replace the existing filter with another exhibiting greater selectivity and change the valve of a few resistors. Filters are available with any degree of selectivity that may be required in the two-way communications



The Sharp, Controlled Selectivity of the Permakay Filter Allows Only the Desired Channel Signals to Reach the Detector.

receiver. At the present time, Permakay filters are designed for deviations of 5, 7.5 and 15 kc (a 40-kc deviation filter is used in 900-mc receivers).

Filter Design

All filters are designed to pass a specific band of frequencies and to attenuate all others. The boundary or frequency between the attenuated band and the passed band is called the "cutoff" frequency. Filters are divided into four classes, according to the frequencies to be passed. These are: low pass, high pass, band pass and band elimination. The IF filter in a receiver is a band-pass filter. It passes a specific band of frequencies and attenuates all others. Because there is no amplification these filters are often termed "passive filters".

Because there is always some loss due to resistance, all filters attenuate the signal to some extent. Attenuation of the desired signal in a passive filter is called "insertion loss". The input and output impedances of the filter must be held constant and they must match the impedances of the terminating circuits. By maintaining a constant impedance match, there are no reflections and the only losses are those due to resistance.

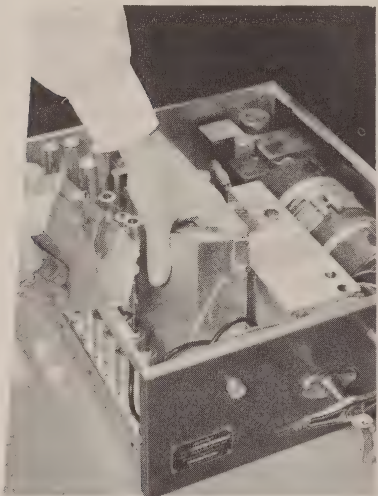
Filters are divided into "T" and "PI" types as shown in figures 7A and 7B. The impedances of the series and parallel section of these filters are designated Z1 and Z2 respectively. The equivalent circuits are shown in figure 8. Where two series-connected units make up the total series impedance as in figure 8A, the impedance of each unit is one-half that of the total series impedance. In a similar manner, the two parallel branches of figure 8B must each have twice the required impedance for the parallel section of the filter.[2]

The Constant "K" Filter

The simplest and most common kind of filter is the "constant-K" filter, in which the impedances Z1 and Z2 are so related that their product is a constant at all frequencies. (Motorola's trade name, "Permakay", is derived from this characteristic).

The cutoff, in a multisection constant-K filter, is gradual rather than sharp. To offset this, an "M-derived" filter may be used. This type of filter section is patterned after a constant-K, but it is provided with a sharper cutoff by the addition of tuned elements either in shunt (parallel) or in series. High attenuation will then occur at some frequency beyond the cutoff frequency. Two types of M-derived sections are possible.. If the extra circuit is in series it is known as a "series derived" section, but if the added elements are in parallel the section is called "shunt derived".

[2] See TM 11-681 Electrical Fundamentals, pages 106-108.



The Permakay Filter in the Motorola Receiver May Be Easily Replaced.

A filter may be made up of any number of sections. The amount of attenuation of the rejected band depends directly on the number of filter sections, and the shape of the transmitted band depends upon the type of sections used. In multisection filters, a "uniform" filter is one having identical sections, while a "composite" filter is made up of two or more sections having different characteristics. In the latter case, each section is designed so as to add a particular operating characteristic to the filter response. A sharp cutoff section usually has a gradual attenuation beyond the cutoff frequency. When it is necessary to have a high attenuation of all frequencies beyond cutoff, a different type of section is added to the filter. In this manner, the bandpass may be designed to meet the requirements of the equipment. For filters requiring a very narrow bandpass, more filter sections are used.

In the case of composite filters, it is important that the impedance of one section match the impedance of the next in order to avoid reflections and losses which would impair the transmission response. Similarly, the end impedances must be properly terminated for best operation. The M-derived section is particularly efficient in matching the impedances of other M-derived section and constant-K sections.

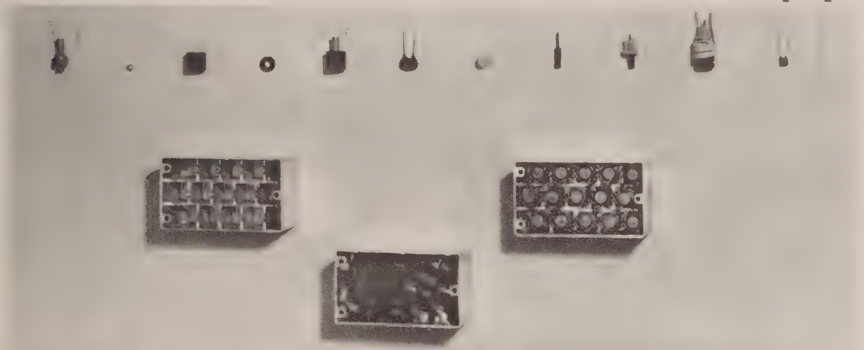
The Permakay filter may have as many as 15 tuned circuits, where operation is on a narrow bandwidth and there are other transmissions on adjacent channels. Filters operating on narrow channels are compensated in order to avoid excessive frequency drift due to temperature changes. Some variation cannot be avoided, but where the channel is very narrow this must be minimized. The filter is not subject to detrimental factors such as weather conditions, and for this reason it should be the last part of the receiver to inspect when trouble arises. From a service standpoint, the simplest way to check the operation of a suspected filter is to substitute another, known to be good, and compare their operation.

Our discussion of filters has now brought us to the point where we are ready to discuss selectivity curves, but this entails some knowledge of the decibel. The student who feels that he is perfectly familiar with this subject may omit the two sections which follow, proceeding directly to the section headed "Selectivity Curves". Students requiring a review of this important subject, however, as well as those who have not had an opportunity to study the decibel before beginning this training, will profit by a careful reading of the following sections, headed "Introduction to Decibels" and "Decibel Reference Level", respectively.

Introduction To Decibels

There is probably no field of electronics today which makes more use of the decibel than does two-way communications. Overall gains, selectivity curves, noise levels and many other factors are all expressed in decibel levels, gains, or losses. The serviceman must have a good working knowledge of decibels, abbreviated db, in order to perform his duties intelligently. The decibel is often concerned with sound intensities, and there is a direct relationship in our hearing to the decibel. Thus, we have a convenient starting place for our discussion.

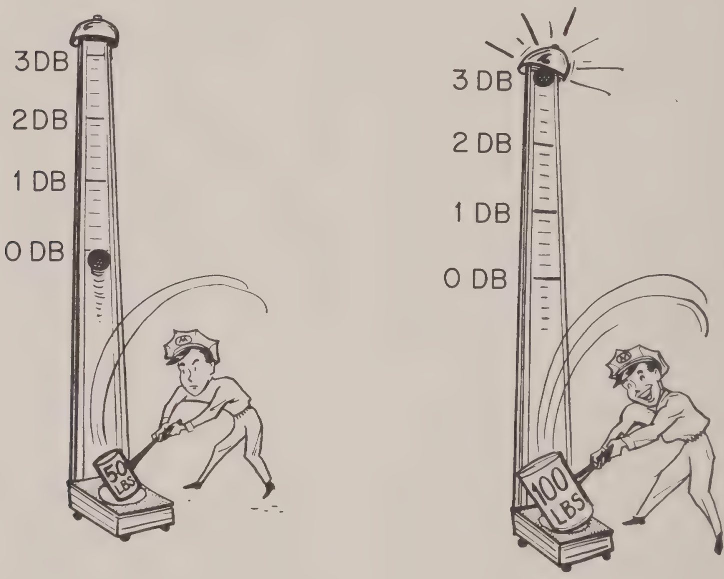
The physicist defines sound in terms of the wave motion or condensations and rarefactions that take place in air. From the physiological standpoint sound is the sensation produced in the ear by such wave motions. There is a difference in the amount of sensation as recorded by the ear as compared with the amount of energy used to produce these sound waves. In other words, our ears are neither reliable nor efficient in distinguishing between sound intensities. For example, will 10,000 people shouting sound 100 times louder than 100 people



The New Die-Cast Filter is Much Smaller, Yet it Gives the Same Performance as Larger Models. Here We See the Separate Parts Used in This Filter and the Complete Assembly Before it is Potted.

shouting? The answer is NO. The difference to our ears is only about 20 times louder. There are many such examples that illustrate the non-linear hearing characteristics of the human ear.

As a further example in comparing sound levels, a sound producing device increasing to twice its original power output produces a 3-db increase in intensity. Any time "power" is doubled



In Electronics, a Power Ratio of Two-To-One is a Difference of 3 DB.

The specific relationship between the amount of sound energy and the intensity of what we hear is conveniently expressed in terms of decibels. The decibel is said to be the smallest change of sound intensity that the human ear can detect; moreover, the conditions must be ideal, or a change of sound intensity of one decibel may not be noticeable. This is a rather non-technical definition but it illustrates how the decibel is used.

it represents an increase of 3 db. Should the power be reduced to one-half its original value, there will be a 3-db loss; the power is said to be "down 3 db". This 3-db relationship holds true whether the level is but a small portion of a watt or many thousands of watts. For example, assume that the power from a speaker is increased from 1 to 2 watts. This is a 3-db change. On the other hand, when the power output from a commercial broad-

cast station is increased from 10,000 to 20,000 watts, the increase again is just 3 db. In the first instance it required only 1 watt to double the power and produce a 3-db gain; in the second case, 10,000 watts were required to cause the 3-db increase.

The exact amount of db change is usually found by means of logarithms. Where two power levels are concerned, the formula is:

(1) db = 10 times the log of P1/P2.

Where voltages (or currents) are being considered, the formula is:

(2) db = 20 times the log of E1/E2 (or I1/I2).

In using either of these formulas, place the larger number in the numerator in order that the ratio will be larger than 1. If amplification has taken place, the answer is said to be a db gain; if there has been some attenuation, the result is the db loss.

EXAMPLE 1.

Find the db change for a power increase from 5 watts to 10 watts.

Using formula (1),

db = 10 times the log of 10/5, or 2.

from a log table, the log of 2 is .3010.

Substituting,

db = 10 times .3010, or a 3.01-db increase.

If the power had been reduced from 10 to 5 watts, the solution remains the same, but this would be a 3-db loss instead of a gain.

EXAMPLE 2.

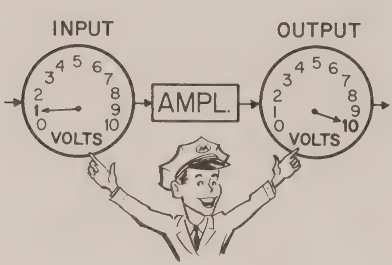
Find the db change when the voltage in a circuit is reduced from 16 to 2 volts.

Using formula (2),

db = 20 times log 16/2, or 20 times log of 8.

The log of 8 is .9031, and the db loss is 20 times .9031, or about 18 db.

The convenience of using decibels may not be apparent in the foregoing examples, but consider the problem of determining the total gain (amplification) of a communications receiver where the gain might easily be 1,000,000. Without decibels, the gain of each separate stage is determined, and then the gains of the individual stages must be multiplied. When the gain of each stage is given in terms of the equivalent db, the separate db gains are added (or subtracted, in the case of a loss).



When the Impedances are the Same, a 10-to-1 Increase in Voltage is a 20-DB Gain.

The decibel also eliminates the use of large, unwieldy numbers. Let's take as an example the receiver having a gain of 1,000,000. What is the db gain? Fortunately we do not have to resort to math when graphs such as figure 9 are available. The vertical scale is laid out in decibels, and along the horizontal scale we find ratios from 0 to 1,000,000. Two "curves" are given, one for voltage and current ratios and the other for power ratios. In order to find the corresponding db gain (or loss) for a given ratio, locate the specific ratio on the horizontal scale, follow the line up to the proper curve and then read the db value directly to the left. For the problem of a voltage gain of 1,000,000 we use the last horizontal division to the right, follow up to the voltage curve and then read the corresponding db change to the left. This is 120 db. As this represents receiver amplification, there is an increase of 120 db.

From the current and voltage curve of figure 9, we can find values such as these:

Current or voltage ratio	db change
10	20
100	40
1000	60
10,000	80
1,000,000	100

From this we see that each time the voltage is increased 10 times, there is a 20-db gain.

From the power curve of figure 9 we get these values:

power ratio	db change
10	10
100	20
1000	30
10,000	40
100,000	50
1,000,000	60

Each power increase of 10 times is a 10 db gain. It is interesting to note that the voltage (or current) db change for any ratio is always exactly twice the corresponding db power change.[3]

Decibel Reference Level

To say that the power of a transmitter has increased 1 watt does not tell us very much unless we also know the power level before the increase took place. When this increase occurs for a

[3] See TM 11-662 Theory and Applications of Electron Tubes, pages 138-139; also Test Methods, pages 3-50 to 3-53.

low power device having but 1 watt of power originally, the increase of 1 watt means a doubling of the power and a 3-db increase.

Should the same increase of 1 watt occur in a transmitter with an original output of 20 watts, the power will now be 21 watts. The effective increase is only 0.2 db and will not be noticeable. An increase or decrease can always be accurately stated in terms of decibels, for this is always a comparison of two levels and automatically indicates the effective increase.

It is not uncommon to find a reference such as "-40 dbm". This rating must assume a standard reference level, and in the electronics industry the value of .001 watt (1 milliwatt) is taken to be the reference or 0 dbm (across 600 ohms).

The level is 40 db lower than .001 watt and 40 db represents a power ratio of 10,000. This means that the power level is 1/10,000 of .001 watt, or .0000001 watt. With the power level known and a standard impedance of 600 ohms, the voltage can be determined from the formula, $E=\sqrt{WR}$. Substituting, the voltage is .0077 volt.

Things to remember about decibels:

1. The decibel is always a comparison between two levels, whether these refer to voltage, current or power.

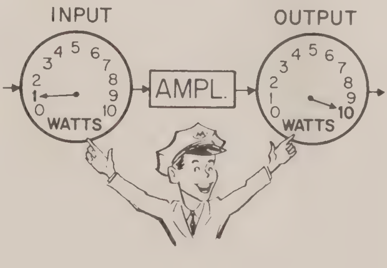
2. An increase (or decrease) of power to twice (or one-half) the original value is a 3-db change.

3. Each change of power by ten times means a 10-db change.

4. Each change of voltage or current of 10 times is a 20-db change.

5. Our ears are not linear devices, but hear intensities according to the db change in power levels.

6. Where a reference level is not specified, .001 watt across 600 ohms is assumed. ("O" dbm is .001 watt.)

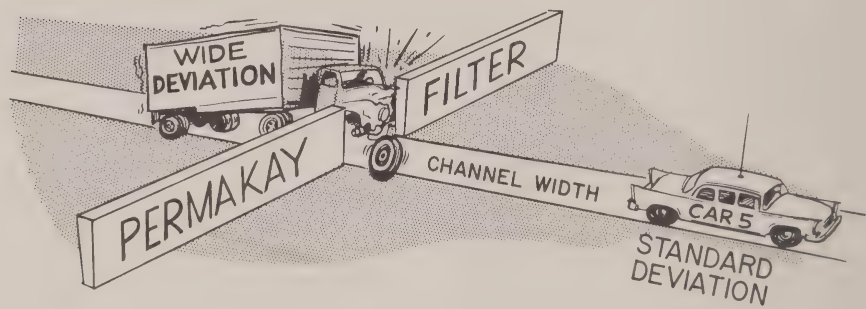


A 10-to-1 Increase in Power is a 10-DB Gain.

Selectivity Curves

Figure 10A illustrates several terms which are commonly employed in connection with selectivity curves. The horizontal

scale is divided according to frequency, and at point "O" we find the center of the operating or reference channel being considered. Because the deviations of the operating channel extend 15 kc to each side of center, the "deviation bandwidth" is 30-kc wide.



Excessive Deviation Cannot Pass Through the Permakay Filter.

The channel spacings are 40 kc apart, so the "adjacent channels" are found 40 kc above and below the center of the reference channel. The next channels are called the "alternate channels" and are found 80 kc above and below the reference channel frequency. The adjacent and alternate channels also have a deviation bandwidth of 30 kc, so this leaves a 10-kc spacing between the deviation limits of adjacent channels. This spacing is referred to as the "guard band".

Figure 10B shows the same channel assignments, the deviation being ±15 kc with a 10-kc guard band. (This is the present channel assignment for "low-band" communications which extends from 24 mc to 54 mc.) The selectivity curves of two receivers are included in figure 10B. The receiver with the "X" filter has an acceptance or operational characteristic which allows not only the desired channel frequencies to get through, but also those of the adjacent and the alternate channels. This receiver will not operate satisfactorily when there are transmissions on the other channels. The receiver with the "W" filter rejects all of the signals on the alternate channels, but there is some response to the deviations within the adjacent channels. Unless there are strong local signals on the adjacent channels, however, this receiver will operate satisfactorily. The "X" filter curve represents the typical response of a receiver incorporating only

conventionally tuned circuits. The other receiver has a response curve for one particular Permakay filter, already discussed in this lesson.

Figure 10C shows the channel spacing for the new "split channel" operation, which has been authorized by the FCC and which will be placed into effect for the high-band, between 162 and 172 mc.[4] The former spacing of 60 kc has been cut in half, so there is but 30 kc between channel assignments. Furthermore, the deviation has been reduced to 5 kc, making the deviation bandwidth 10 kc. The guard band is then 20 kc.

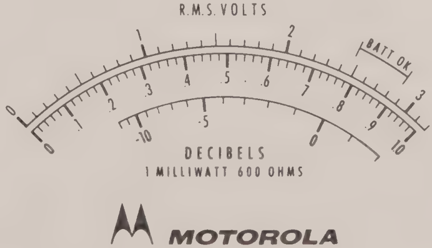
The selectivity of the W filter discussed for figure 10B is shown in figure 10C. From the figure it is evident that the W filter will accept a considerable amount of energy within the adjacent channels. Thus, the W filter is not satisfactory for this mode of operation, and a filter having a greater amount of selectivity is needed. The desired adjacent channel rejection is indicated by the curve of the S filter--this Permakay filter has been designed to furnish the sharp selectivity required for split channel operation. Only those signals of the operating channel are accepted by the filter and passed on to the last IF amplifiers and discriminator.

A note of interest here is the additional requirements for the receiver and transmitter that operate on these extremely narrow channels. The receiver high-frequency oscillator must be extremely stable or a resulting intermediate frequency shift will be beyond the acceptance of the filters. In addition, the deviation at the transmitter must be under control or the deviation bandwidth will be excessive, spilling over into the adjacent channels. (Frequency drift in the transmitter is just as undesirable as in the receiver).

The curves of figure 10 are not complete in describing the filter since they do not specify the amount of attenuation taking place in the various channels. Unless we know how much the adjacent channel signals are attenuated we do not accurately know the effectiveness of the filter.

DB Ratings For Selectivity Curves

Figure 11 shows representative selectivity curves for two receivers having different de-

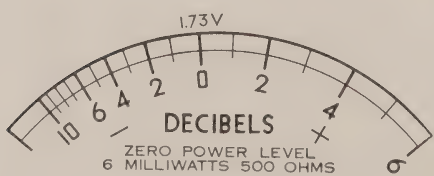


The DB Meter Dial Markings Are Actually Voltage Readings Calibrated According to Power Level.

[4] The FCC has since ruled that many of the channels in both the high band and low band will be converted to split-channel operation. See "Utilizing the New Split Channel Mobile Frequencies," and "The Split Channel Story."

grees of selectivity. The attenuation of the off-channel frequencies, to the left of the figure, is stated in decibels, and all comparisons relate to the strength of the signal at the center of the assigned channel. The same amount of signal is applied to the filter input at various frequencies; the output voltage is then measured and compared with the voltage produced at the center frequency. The ratio of the voltages is converted to the equivalent db rating and plotted on the graph. For comparison purposes the center frequency has zero attenuation, as shown at the bottom of the vertical scale. The higher we read on the vertical scale, the greater the attenuation.

The curve representing receiver No. 1 is relatively flat for frequencies up to 10 kc on each side of center, but at 15 kc it rises sharply and the attenuation is about 100 db. This means the receiver will satisfactorily reject all signals of the adjacent and alternate channels. The selectivity of receiver No. 2 is not as satisfactory as that of No. 1. The attenuation for the center of the adjacent channel is only 40 db. An attenuation of 40 db is a voltage ratio of only 100 to 1, insufficient to prevent a signal of reasonable strength from causing interference. Adjacent channel deviations receive even less attenuation, making the interference problem correspondingly greater. The 100-db attenuation of adjacent channel signals provided by receiver No. 1 represents a voltage ratio of 100,000 to 1 (see the graph of figure 9), and this is entirely satisfactory even in the presence of strong signals from transmitters operating on adjacent channel frequencies.

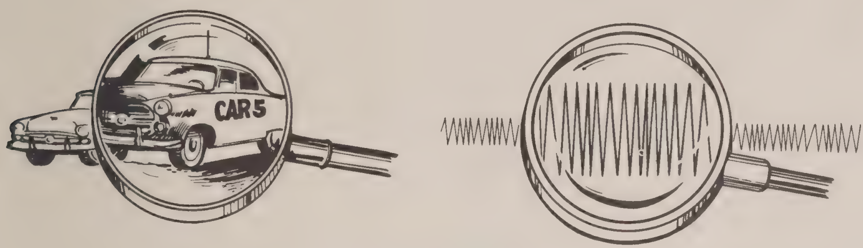


Some Meter Dial Scales Use 6 Milliwatt (.006 Watt) and 500 Ohms as the "0-DB" Reference.

Selectivity curves are occasionally drawn differently from the way they appear in figure 11. One method is to reverse the vertical scale, so that zero attenuation appears at the top and maximum attenuation at the bottom. The curves will be the same as in figure 11, but "upside down". In analyzing any attenuation curves or selectivity graphs, the important factors to note are the amount of attenuation and the frequency spread--unless these are well defined, the curves or graphs will have little significance.

The IF Amplifier Curcuit

The major requirements of the second IF amplifier section, as stated in the beginning of this



AMPLIFICATION "MAGNIFIES"

lesson, are to provide (1) a high degree of selectivity and (2) considerable amplification ahead of the limiters. By dividing these functions into separate operations, as performed by the Permakay filter and the IF amplifier strip, respectively, the requirements are realized most efficiently. We have studied the Permakay filter and its ability to provide a high degree of selectivity; we are now prepared to consider the second requirement --amplification.

The greatest portion of the receiver gain or amplification is realized in the three-stage IF amplifier strip following the Permakay filter (figure 12). This section of the receiver has more than sufficient gain to produce full saturation of the limiters on all signal input levels. Thus the second IF section provides a certain amount of "reserve gain" for the receiver. Reserve gain means that any normal reduction of amplification due to tube aging and similar causes will have no appreciable effect on the overall operation of the receiver.

Figure 12 shows a typical Motorola circuit. The three stages incorporate high-gain pentode type tubes. Since the filter has provided all the necessary selectivity, the IF amplifier strip may be designed for maximum gain and stability. Our only interest in selectivity at this point is to make sure that the tuned plate circuits which are used to obtain a higher gain are not too selective; otherwise they might reject some of the desired sidebands of the channel signal!

This IF strip does not differ materially from most well-designed high-gain voltage amplifier stages. Comparatively low plate and screen voltages, together with excellent decoupling, good design practice and parts placement, minimize the feedback, thus stabilizing the amplifier. The first amplifier stage uses cathode bias to insure maximum gain, but the second and third stages have grid-leak bias. Use of grid-leak bias produces some limiting action, particularly in the third stage in the presence of a strong signal. The nega-

tive voltage resulting from the grid-leak bias on this stage is often used as a source of negative AGC voltage, which is applied to the grid of the RF amplifier. (Grid-leak bias will be discussed in detail in the lesson on "Limiters", which follows).

In operation, the output of the filter is applied directly to the grid circuit of the first IF amplifier stage and the overall amplification of the IF strip is likely to be in excess of 1,000,000, representing a gain of at least 120 db.

IMPORTANT WORDS USED IN THIS LESSON

CRITICAL COUPLING: That amount of coupling between tuned circuits which allows for maximum output voltage, but which retains relatively sharp selectivity.

CUTOFF FREQUENCY: As applied to filters, the cutoff frequency is the midpoint between the attenuated band of frequencies and the passed band of frequencies.

DBM: A decibel reference level, in which .001 watts across 600 ohms equals zero dbm. All power levels may then be stated with respect to this 1 milliwatt reference.

DECIBEL: A standard unit of comparison between two levels of sound intensities or electrical power. A decibel is sometimes defined as "the smallest change of sound intensity that the human ear can distinguish."

FILTER: A frequency selective device in which certain frequencies are allowed to pass, but other frequencies are attenuated.

INSERTION LOSS: Attenuation of the desired signal in a passive filter; it is usually stated in decibels.

PASSIVE FILTER: A filter not having any internal amplifying device.

"PERMAKAY" FILTER: The registered trade mark given to the highly selective filter developed by Motorola and incorporated in the last IF section of a receiver in order to provide sharp selectivity.

STUDENT NOTES

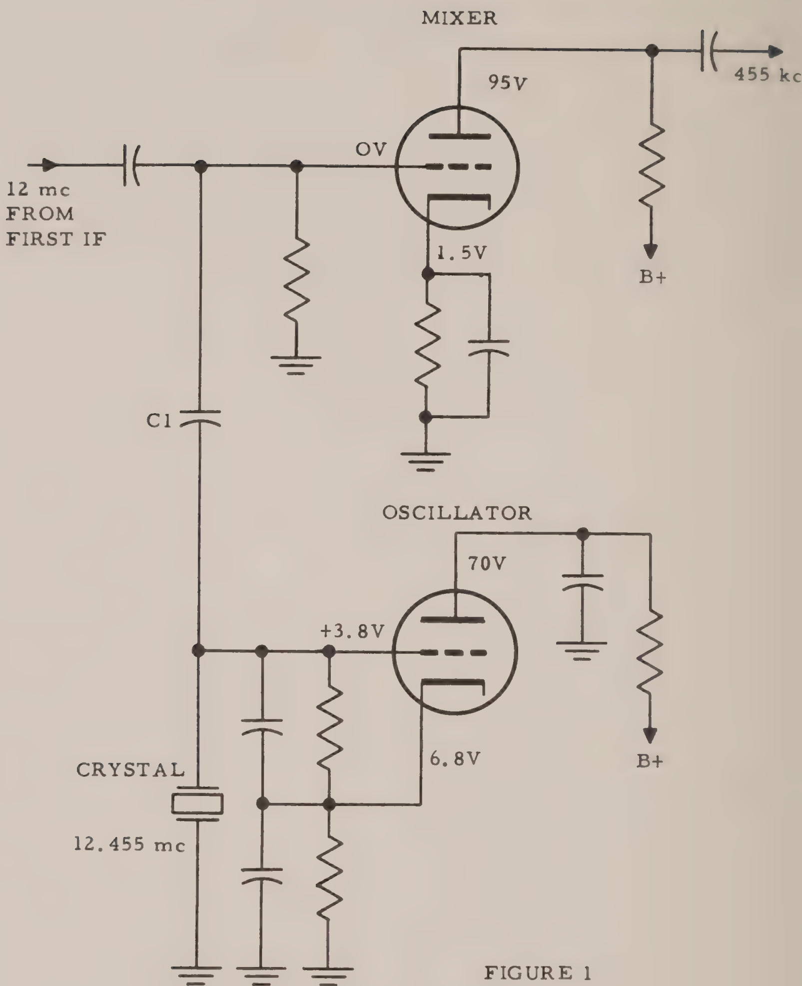
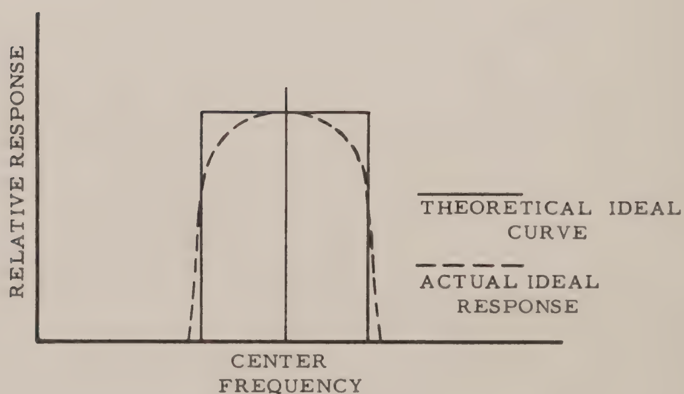
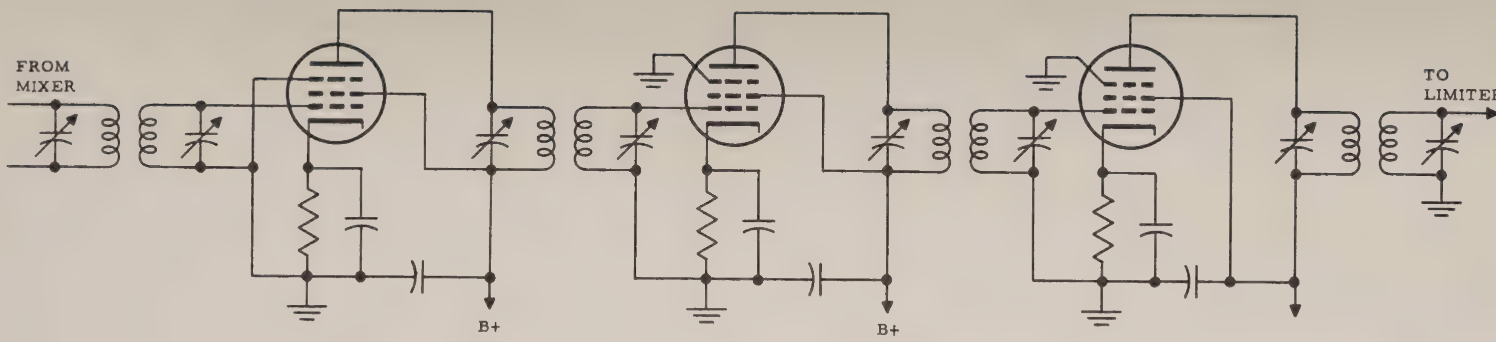


FIGURE 1



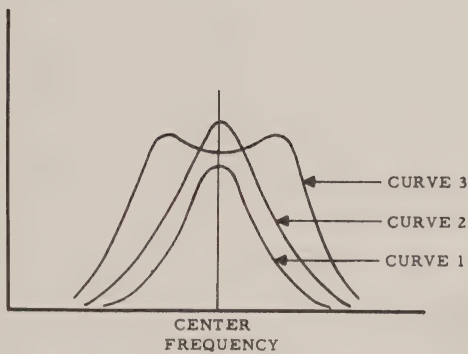
IDEAL SELECTIVITY CURVES

FIGURE 2



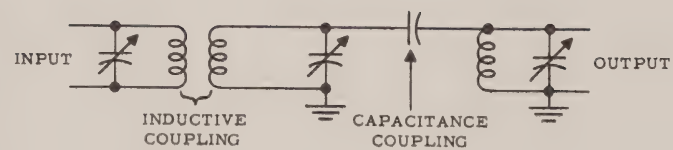
IF AMPLIFIER

FIGURE 3



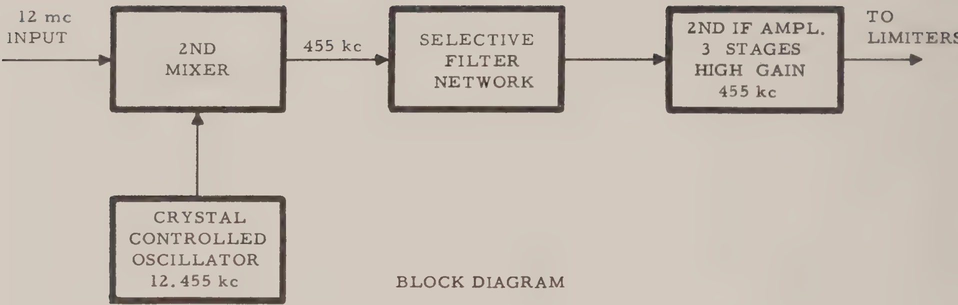
TRANSFORMER COUPLING CURVES

FIGURE 4



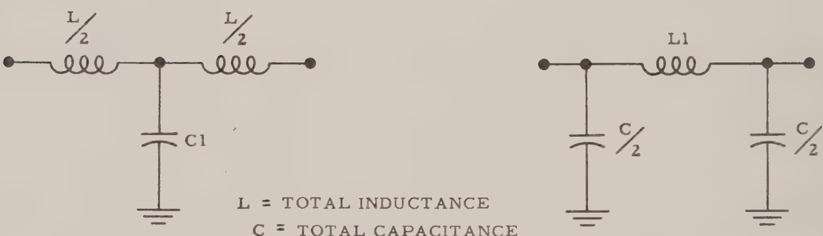
"TRIPLE TUNED" TRANSFORMER

FIGURE 5



BLOCK DIAGRAM

FIGURE 6



"T" FILTER
FIGURE 7A

"PI" FILTER
FIGURE 7B

FIGURE 8A

FIGURE 8B

DEFINITIONS

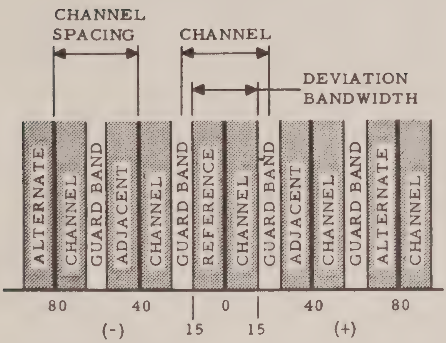


FIGURE 10A

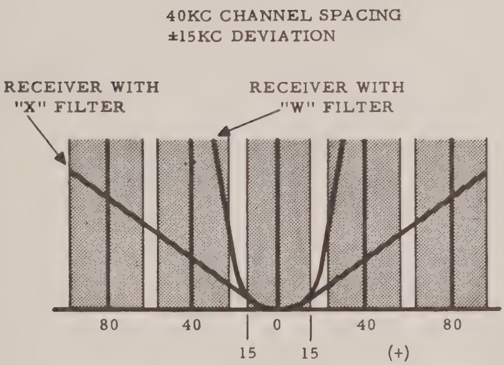


FIGURE 10B

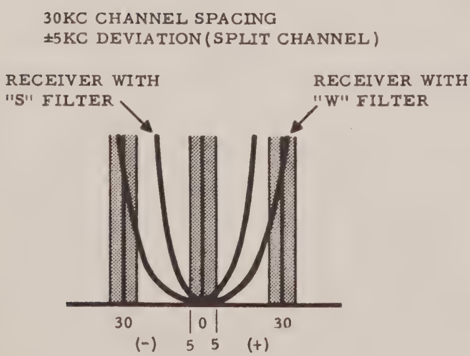


FIGURE 10C

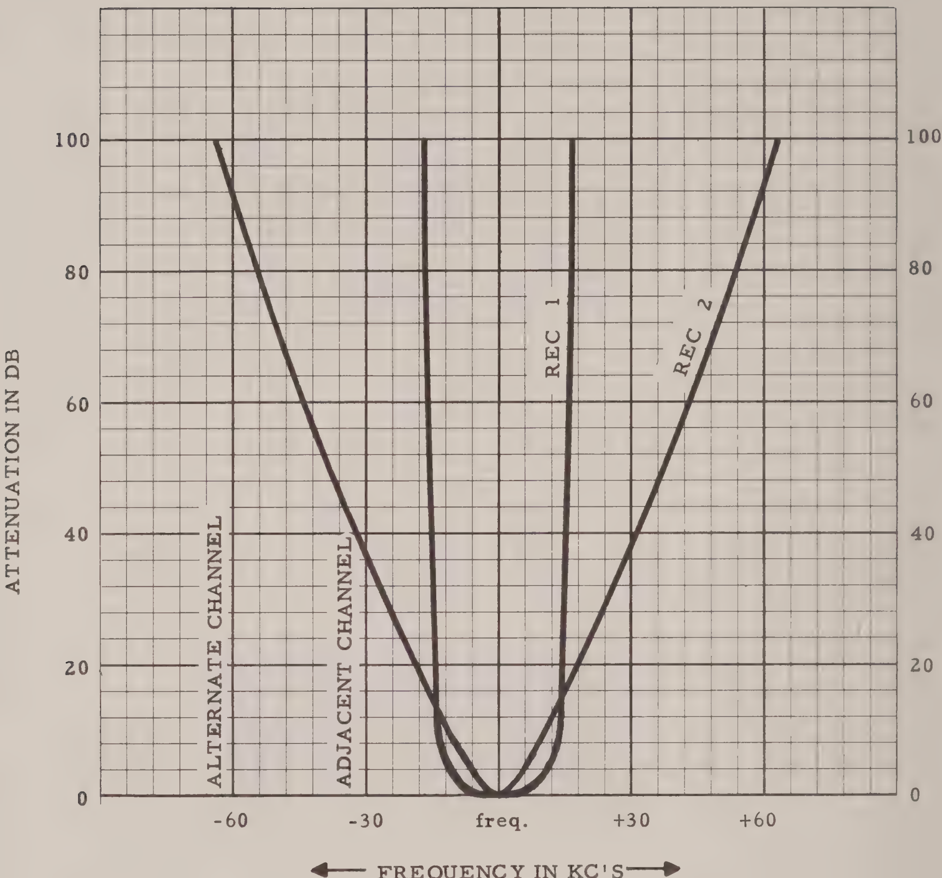
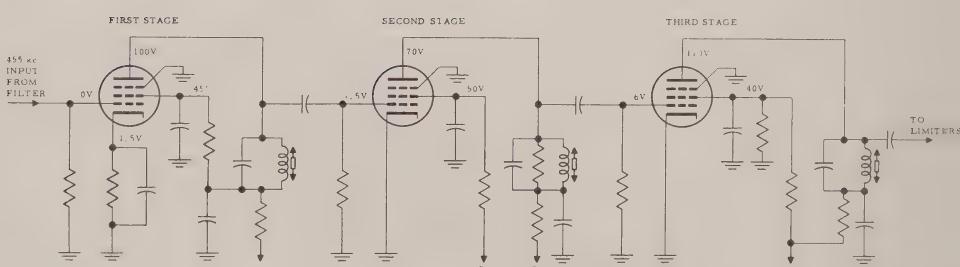


FIGURE 11
OVERALL RECEIVER
SELECTIVITY



IF AMPLIFIERS - 455 kc
FIGURE 12

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Name ______________________ Student No. ______

Street ________________ Zone ____ Date ______

City ______________ State ________ Grade ______

Examination, Lesson RA-5

1. The purpose of the second oscillator, mixer, filter and IF sections of a receiver is (choose two answers).

   A. To reject the image frequency. A. ______
   B. To prevent intermodulation. B. ______
   C. To reject adjacent channel signals. C. ______
   D. To provide high gain. D. ______

2. The incoming signal to the last oscillator-mixer of a receiver is 11 mc. In order to provide a second IF of 455 kc, the oscillator frequency may be either ______________ or ______________.

3. For the conditions of question 2, the image frequency operative at the last mixer may be either ______________ or ______________.

4. Why is it necessary for the selective receiver to have a response curve closely resembling that of Figure 2? (Check all correct answers).

   A. To reject adjacent channel signals. A. ______
   B. To accept all the signal deviations. B. ______
   C. To avoid distortion. C. ______
   D. To have high amplification. D. ______

5. What is the advantage of using a filter such as the Motorola PERMAKAY filter instead of tuned transformers as shown in Figure 3? (Indicate all correct answers).

   A. Tuning procedure less complicated. A. ______
   B. Better selectivity. B. ______
   C. Greater stability. C. ______
   D. Easy to adopt receiver to narrow band operation. D. ______

6. Indicate True or False after each of the following statements concerning filter design and operation.

   A. It is important that the impedances of the terminating circuits match the impedances of the filter. A. ______
   B. The "insertion loss" of a filter refers to the attenuation of undesirable signals. B. ______
   C. More tuned circuits in the filter means greater sensitivity. C. ______
   D. The filter provides most of the receiver's overall selectivity. D. ______

7. A power increase of 100 per cent means an increase of ______________ db.

8. The signal input to a receiver is 0.6 microvolt (uv) and the front end has a gain of 40 db. What is the output voltage?

   A. 60 volts ______________ C. 0.0006 volt ______________
   B. 600 microvolts ______________ D. 0.00006 volt ______________
   E. All of these are incorrect; the answer is ______________.

9. The operating frequency of a receiver is 151.55 mc. With 40-kc assignments.

   A. The adjacent channels are ______________ and ______________.
   B. The alternate channel frequencies are ______________ and ______________.

10. Underscore the correct words in the following:

    Figure 12 is the schematic diagram of a (high)(low) gain (IF)(RF) amplifier. The main purpose of the amplifier is to provide (selectivity)(gain) for the receiver. The tuned circuits are adjusted for (maximum)(minimum) signal at the following stage.

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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-6
FM RECEIVERS

The Limiter

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-6
FM RECEIVERS

The Limiter

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
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DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

THE LIMITER

LESSON RA-6

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

On-the-spot reporting of news events, sports and other public affairs is made possible by lightweight hand-carried "Handie-Talkie" transmitter-receiver units right at the scene of action. As emergency devices they may also be used for coordinating traffic or crowd direction or for summoning medical or other aid.

THE LIMITER

Lesson RA-6

Introduction

The noise-free reproduction of weak signals by the FM communications receiver is made possible by the operation of its limiters. While the discriminator is designed to respond to the incoming deviations of the applied signal, it is also sensitive to amplitude variations--and the dominant characteristic of all noise energy is its amplitude irregularity. Thus, by providing a signal of constant amplitude to the discriminator, the limiter makes possible the relatively noise-free reception of FM signals.

Limiter Action -- General

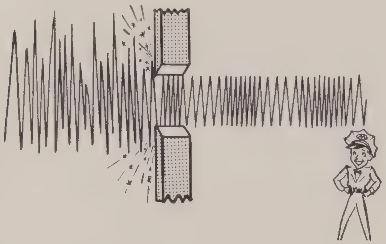
Figure 1 illustrates the effect of the limiter on the FM waveform. The incoming signal at the left contains many irregular amplitude variations in addition to the desired frequency modulation. Most of the noise energy is concentrated on the peaks of this signal. To eliminate this noise energy from the signal, the peaks of both the positive and negative portions of the signal must be removed before the signal reaches the discriminator.

At the right in figure 1, we see the output waveform, represented by pulses of plate current. Only a small portion of the positive half-cycle of the incoming signal is reproduced in the output--the entire negative half-cycle and the peaks of the positive excursions have been eliminated.

The limiter has upper and lower limits, as represented by the aperture in the figure--regardless of the amplitude of the applied signal, the output can never exceed these limits. For proper operation, however, it is essential to provide a signal of high amplitude into the limiter. Otherwise the waveform may not be clipped to any great degree, and considerable noise will still reach the discriminator.

The desired limiting action, as illustrated by figure 1, may be secured by various means; (1) diodes can be inserted in the signal path so that they become conductive when the output voltage is at the predetermined value; (2) a large resistor can be placed in series with the signal input to the grid to attenuate the positive peaks of the input signal, allowing at the same time the negative

peaks to pass unaltered; (3) a plate -- or "saturated" -- limiter can be used. Because almost all FM communications receivers use this last type of limiter, it is the only one we shall discuss in this lesson. [1]



When a "Strong" Signal is Applied to the Limiter the Output Has a Constant Amplitude. This Means that the AM Noise Has Been Eliminated.

The Plate Limiter

The plate limiter is characterized by; (1) the use of low plate and screen voltages, and (2) grid-leak bias. The term "plate limiter" is descriptive of the requirement that each incoming FM wave must cause the limiter to operate between plate saturation and cutoff. The alternate term--"saturated limiter"--is even more descriptive, as we shall see.

The incoming signal, in order to "drive" the limiter to full saturation, must have a very high amplitude -- the higher the better. Most limiters reach the saturating point when a signal of about two or three volts is applied. Assuming that the weakest signal to be received measures 0.5 microvolt at the antenna, the total amplification preceding the limiter must be at least 4,000,000 in order to provide a two-volt signal at the limiter. This is a minimum gain of 132 db (1,000,000 is 120 db, and 4 is 12 db).

Even when the signal applied to a limiter is strong enough to cause saturation, there is some noise energy remaining in the output. To secure additional noise reduction or limiting--it is not possible to have too much--most communications receivers include two or more limiters in "cascade." (Cascade means that the output of the first stage is applied to the input circuit of the second stage.)

The Limiter Circuit

The typical pentode limiter shown in figure 2 uses a grid resistor and capacitor to provide grid-leak bias, and large resistors in the plate and screen circuits to reduce the operating voltages to a low value. Because of the low plate and screen voltages--usually about 50 or 75 volts--only a small change in grid voltage is required to swing the plate current between saturation and cutoff. The plate current cannot increase beyond maximum (saturation), nor can it decrease to less than zero (cutoff). Thus, all plate-current pulses have the same amplitude and, since each cycle of grid voltage produces one pulse of plate current, these plate-current pulses correspond in frequency with the frequency of the incoming signal.

1. See TM 11-668 FM Transmitters and Receivers, pages 155-156; also FM Transmission and Reception, by Rider and Usland, pages 277-280.

The grid resistor-capacitor combination plays an important part in the operation of the limiter because of the automatic bias it supplies. In the absence of any signal (or noise), there is no bias. As soon as a signal is applied, however, the grid becomes negative as a result of the bias developed by the grid capacitor and resistor, and the amount of bias changes automatically according to the strength of the signal. This subject of grid-leak bias is discussed in detail later in this lesson, but it is introduced at this point because it is necessary to know that the amount of bias is determined by the strength of the incoming signal. Figures 3A, 3B, and 3C represent limiter operation for different values of signal input, indicating the degree of bias developed in each case.

In figure 3A the signal is weak, and the resulting grid-leak bias is somewhere near the straight portion of the plate-current curve. The amplitude of the signal is insufficient to swing the grid either to the point of plate-current cutoff or beyond the point of saturation. The output plate-current pattern is a reasonable reproduction of the grid-voltage waveform, and the stage provides some amplification. The limiter stage may thus operate as an amplifier for very weak signals. (This condition is not likely to exist in the modern, sensitive FM communications receiver, however, for the amplification preceding the limiter is such that the input will be greater than that of figure 3A.)

In figure 3B the signal is somewhat stronger, and this stronger signal produces a larger bias--near cutoff. During the negative portion of the input signal, the negative grid voltage is greater than the cutoff value and there is no plate current. Plate current takes place during the positive portion of the RF cycle, but the positive peaks are clipped, due to plate current saturation. When the limiter is operated in this manner-- with part of the cycle missing in the output waveform--noise voltages occuring during this "clipped" time are eliminated. This clipping action is good, but for our purpose it is not good enough. For best limiting action, the applied signal must be greater than that shown in figure 3B.

In figure 3C the input voltage is much stronger. The bias is well beyond plate-current cutoff and plate current does not take place during any portion of the negative alternation. In fact, plate current occurs during only a small portion of the positive alternation, and the positive peaks are severly clipped. This is the normal operating condition for a limiter employing grid-leak bias.[2] Let us see, now, how this grid-leak bias works.

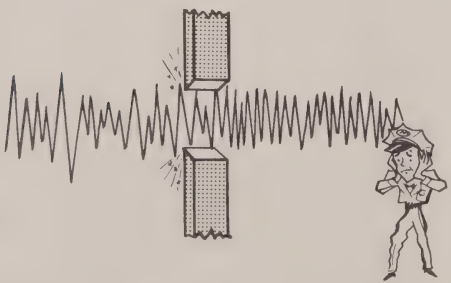
Grid-Leak Bias Operation

In the absence of a signal or noise voltage at the grid, there is no grid-leak bias. As soon as a signal (or noise voltage) is applied, the grid becomes negative. The amount of this negative bias is

2. See TM 11-668 FM Transmitters and Receivers, pages 156-158; also FM Transmission and Reception, by Rider and Uslan, pages 280-292; also TM 11-672 Pulse Techniques, pages 17-20.

variable, being determined at all times by the strength of the signal. This incoming signal, being AC, is continually changing polarity.

Figure 4A represents grid-leak operation during the positive alternation of the incoming signal. This positive voltage drives the grid positive with respect to the cathode, and the grid draws current from the cathode. This current charges the grid capacitor to a value nearly equal to the positive peak voltage of the applied signal, making the grid negative. (The charging path and direction are indicated by the arrows.) A small part of the charging current can pass through the grid resistor, since it is in parallel with the tube, but most of the current passes through the tube, which offers very low resistance when it is conductive. Because of this low resistance path, the capacitor charges rapidly.



If a "Weak" Signal Reaches the Limiter, Some Amplitude Variations Remain in the Output Waveform and Noise will Still be Heard in the Output.

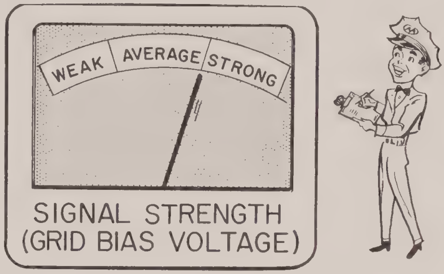
Figure 4B represents the circuit during the negative alternation which follows. The negative signal voltage and the negative charge on the capacitor are in series and the resulting strong negative voltage is applied to the grid, making it highly negative with respect to the cathode. Since there can be no current between the grid and cathode, the capacitor must discharge through the grid resistor; since the resistance of this path is comparatively high, the capacitor discharges slowly.

The conditions shown in figure 4A are repeated on the next alternation, when the signal is again positive, but this alternation finds the grid capacitor still partly charged. The positive signal voltage opposes the charge retained by the capacitor, and the total grid voltage is now the difference between these two voltages. This difference in voltage is negative at the beginning of each alternation, while the signal is building up. Only when the signal nears the peak of its positive swing will it exceed the charge on the capacitor and cause the grid to again become positive. The grid then draws current, but only for a short period of time, and once more charges the capacitor.

Because the signal drives the grid positive during some portion of each cycle and replenishes whatever charge has leaked off the capacitor during the remainder of the cycle, the capacitor accumulates a relatively constant voltage which becomes the "grid-leak bias".

The strength of the incoming signal determines the amount of bias, which must automatically change in value according to the strength of the signal. Another important feature in the operation of grid-leak bias is its effect upon the average plate current. Without any bias the plate current is high--plate current occurs continuously. With a signal, however, the grid is biased to class C and plate current occurs during only a short portion of each cycle. The average plate current is thus reduced. The screen grid current also decreases and for the same reason. With reduced current, the voltage drop across the plate and screen resistors also decreases. The plate and screen voltages must then increase, for they are determined by the "IR" drop of the resistors.

Let us again look at figure 3C, which represents the normal operating condition for a limiter employing grid-leak bias. The incoming signal, shown at the bottom of the figure, has appreciable amplitude and the bias is considerably beyond plate-current cutoff. Plate current does not take place during any portion of the negative alternation, but when the signal swings positive, plate-current pulses occur. At the moment the grid voltage reaches point A on the curve, plate current starts; as the grid voltage swings to the right, plate current increases to a maximum value, at point B. The grid voltage curve continues still further to the right, but plate current cannot increase further as it is already at maximum. The grid voltage next reverses direction, moving to the left. At point B' plate current starts to decrease, reaching zero at point A'. Thus, for each positive excursion of grid voltage, plate current starts at zero and increases to maximum, remains at maximum for a period of time, and finally decreases once more to zero.



A Meter Placed in the Grid Circuit of the Limiter Indicates the Relative Strength of the Applied Grid Voltage, Whether it be Signal or Noise.

Although most of the noise energy tends to concentrate near the peaks of the incoming signal to the limiter, noise is continuous in nature and occurs during the entire portion of the signal waveform. Thus, while good noise reduction is effected by clipping the positive and negative peaks from the signal, it is also important that the noise occuring during the remainder of the cycle does not reach the discriminator. This is realized by minimizing the time it takes for the limiter plate current to change from cutoff to saturation and from saturation back again to cutoff.[3]

3. See TM 11-662 Theory and Applications of Electron Tubes, page 124.

Saturation and Noise Reduction

Figure 5A shows one complete cycle of RF grid voltage, with noise present; figure 5B shows the corresponding plate-current pattern.

Because of its low amplitude, the RF input of figure 5A does not cause ideal limiting action; much of the noise, which is present as an amplitude modulation of the RF, is also present in the plate current (figure 5B). Points A and B on the curve correspond to points A and B in figure 3C. Plate current starts at point A and increases to maximum at point B. During this period of plate-current increase, any noise modulations which are present will appear as variations in the plate current. In a similar manner, the plate current is decreasing between points B' and A', and noise voltages can also get through to the plate circuit during this period. Either of these two periods of time (between A and B or between B' and A') can be thought of as a "gate" which is open to plate-current variations, during which time the tube will accept noise fluctuations. It thus becomes important to shorten the time it takes for the plate current to change from A to B and from B' to A'. Figure 5A also shows several noise pulses falling below the saturation level (between points B and B' on tne curve). These noise voltages, which are present on the positive peaks, also produce variations in plate-current. The plate current pattern of figure 5B shows that noise pulses occur, (1) during the periods of plate-current increase and decrease, and (2) during the period when plate-current should remain at the saturation level.

The waveform of figure 6A is similar to 5A but its amplitude is considerably higher. The difference in amplitude between A and B is restricted to a much shorter period of the cycle; it takes less time for this voltage to change from A to B and from B' to A'.

The gate which was opened to plate-current variations in figure 5A is open for only a short interval in 6A. With the gate open for a shorter period, less noise energy can get through to the plate circuit. Also, noise voltages on the positive peaks in figure 6A are far beyond the saturation level and cannot cause any changes in plate-current. The plate-current pattern of figure 6B shows, (1) very abrupt plate-current changes between zero and maximum, and (2) a steady current for a considerable time. The noise present in figure 6B is considerably less than that in 5B.

While the application of strong signals to the limiter will result in good limiter action and noise reduction, a single limiter stage is generally unable to reach full saturation and provide satisfactory noise reduction when the incoming signal is weak. For this reason, most FM communications receivers employ two limiters in cascade.

Cascade Limiters

A typical Motorola circuit, employing two limiter stages, is shown in figure 7. Resistance coupling between the stages eliminates the use of a transformer, which is always difficult to align where the limiters are in saturation and the adjustment of the circuits to resonance do not cause any additional increase in output voltage. Low values of supply voltage and grid-leak bias are used in both stages and the operation of each is similar to that just described.

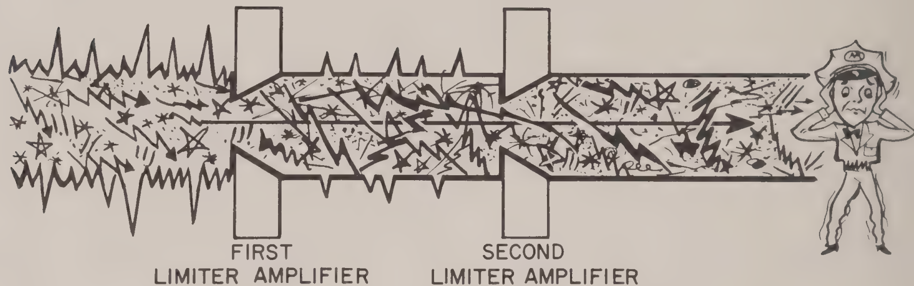
The first limiter, with no signal applied, has an initial bias of approximately 25 volts due to noise. With a signal applied, this bias will increase. The stronger the signal, the higher the voltage produced, until the point of maximum bias-- about 60 volts-- is reached. At this point, the maximum possible signal will be reaching the grid, due to saturation in the plate-circuit of the preceding stage.

The second limiter, with noise applied, has an initial bias of approximately 20 volts. With a signal applied, a bias does not noticeably increase. This indicates that the plate of the first limiter is already saturated by the noise, and the signal produces little or no increase in voltage from this stage. The signal voltage merely replaces the noise voltage in the output.

Strong signals are limited to some extent even before they reach the first limiter. It will be recalled that the last IF stage does not use cathode bias, but has a grid-leak arrangement which provides some limiting action. When a signal is strong enough to exceed the straight portion of the operating curve, reaching the points of cutoff and saturation, the IF stage operates as a limiter so that, in effect, the receiver has three "limiters" on strong signals.[4]

Two Limiter Stages are Usually Employed in the FM Communications Receiver to "Wipe Off" all Amplified Modulation from the Signal to the Discriminator.

4. See TM 11-668 FM Transmitters and Receivers, pages 157-158; also FM Transmission and Reception, by Rider and Uslan, pages 290-292.



The Output Voltage of the Second Limiter Always has the Same Amplitude. In the Absence of a Signal this is "Noise" Voltage.

The Limiter Output -- No Carrier Present

While we know that the output of the limiter section of the FM communications receiver has a constant amplitude, it is well that we investigate the nature of its waveform in the absence of a signal.

Because of the very high gain of the entire receiver, particularly in the last IF section, the small noise voltages generated in the RF stage become large voltages at the limiter. For this reason, the last limiter is always in a state of saturation. Thus, the limiter output, despite the absence of a signal, consists of noise voltages having a constant amplitude. When this waveform is applied to the discriminator the receiver becomes very noisy. This noise output from the discriminator is mainly due to the irregular frequency pattern of the waveform rather than to any amplitude changes.

The Limiter Output -- Carrier Present

When a carrier is received, it "replaces" the noise energy in the output of the limiter. Because of the amplitude-limiting ability of the stage, the noise energy in the plate circuit of the last limiter is reduced. Instead of the irregular noise pulses, the plate current pulses now correspond to the last IF frequency. These pulses of plate current through the primary of the discriminator transformer (tuned to the IF center frequency) cause an oscillatory current within the tuned circuit and a sine-wave voltage results. This circulating current will also occur for frequencies slightly above and below the center frequency (deviations). Thus, the signal applied to the discriminator; (1) is a sine wave of constant amplitude, (2) is noise free, and (3) contains the same deviations as the incoming signal to the limiter.

The completeness by which the signal replaces the noise voltage at the limiter output depends pri-

marily upon the strength of the signal itself; strong signal voltages produce a more complete noise reduction than do weak signals. The exact amount is usually referred to in terms of the resulting "quieting."

Receiver Quieting

As we have already said, when a carrier is received the noise energy at the limiters is "replaced" by the signal--the completeness of this action depends upon the carrier amplitude. The degree to which the noise is reduced is usually referred to as quieting, and is often used in measuring the effective sensitivity of a receiver. Specifically, we use "20-db quieting" in determining the receiver sensitivity. This refers to a 90% reduction in the noise voltage present at the receiver output before the carrier is received. The incoming carrier causes a noise reduction at the limiters, and when the noise voltage, measured at the speaker, is attenuated to 10% of its original value, the noise is 20 db down. (20 db is a 10 to 1 voltage ratio.)

There is no specific minimum amount of quieting necessary in order to understand a message, for, in addition to noise quieting, "readability" depends upon other factors. The ambient noise at the receiver, the experience of the operator and his ability to anticipate what is being said, and the ability of the receiver and speaker to provide full output over the entire voice range of 300-3000 cycles are just a few of the things which must be considered. With 5-10 db of quieting some noise is still apparent, but the message is usually readable. It takes 20 db of quieting, however, before uncomfortable noise is reduced to a fairly low level. At 30-db the noise has been reduced still further--to the point of inaudibility.

20 DB of Quieting is Realized When the Noise Voltage Reaching the Speaker has been Reduced to One-Tenth Its Original Value.

Metering the Limiter

The negative grid-leak limiter voltages are very useful, both to the operation of the receiver, and to the serviceman who makes use of these voltages in his daily work. As far as the receiver is concerned, negative voltages at the limiter grids are used (1) as a source of AGC controlling voltage--already discussed in a previous lesson, and (2) as a negative reference voltage in squelch operation--to be discussed in one

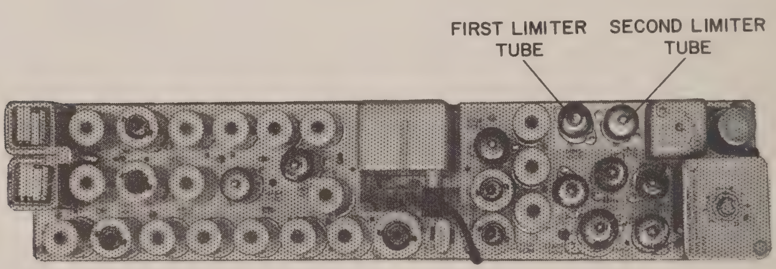
of the next assignments. The serviceman finds two important uses for the negative voltages at the limiter. First, this voltage, as determined by the strength of the incoming signal (up to the point of saturation), becomes a convenient method of determining the relative gain of the entire receiver. Second, this voltage becomes a convenient "output meter" for the entire front-end of the receiver in alignment procedures. Up to the point of saturation, this voltage may be monitored, and the tuned circuits of the preceding stages adjusted to resonance.

Figure 8 shows a typical metering arrangement incorporated in FM communications receivers for the purpose of measuring grid-leak bias. The manufacturer specifies the sensitivity of the meter, usually a 50 micro-ampere movement. The required series-connected resistor is mounted directly on the tube socket, and the meter is protected from RF by means of the bypass capacitor. A plug is provided for connecting the meter to the receiver.

Summary

Amplitude modulation, particularly noise energy, is eliminated from the FM signal by the operation of limiters ahead of the discriminator stage. With low operating voltages on the plate and screen grid, plate-current saturation takes place rapidly. Grid-leak bias is used to operate the tube on the desired portion of the characteristic curve for all levels of applied signals.

To obtain good limiting action, the amplitude of the input signal to the limiter must be appreciable--there must be a high order of amplification in the stages which precede the limiter. Limiting action, by removing both positive



This Photo Shows the Location of the Limiter Stages of a Typical Motorola Receiver.

and negative peaks from the signal, eliminates most noise voltages from the signal.

At least two limiters in cascade are necessary for positive limiting of all signals.

Strong signals saturate the limiter. After limiters reach a condition of saturation, the output voltages no longer increase with signal strength. A constant grid-leak bias at any grid circuit means that the plate circuit of the preceding stage has reached saturation.

The last limiter stage in a high-gain communications receiver is saturated with or without a signal. Without a signal the noise voltage output has a nearly constant amplitude. A signal replaces the noise in the output (noise quieting)--the amplitude remaining constant.

IMPORTANT WORDS USED IN THIS LESSON

CASCADE: Two or more stages arranged so that the output of one is applied to the input of the next stage.

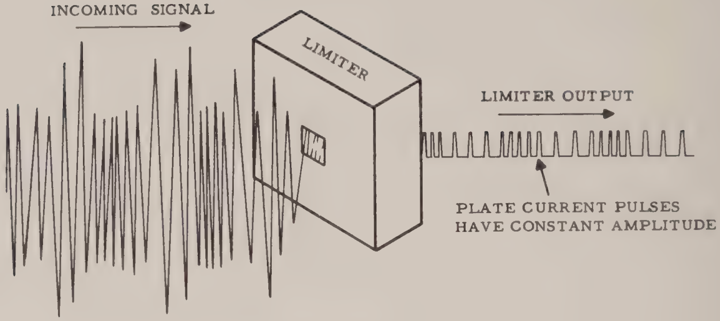
GRID-LEAK BIAS: A biasing method whereby the grid is made negative by an amount dependant upon the strength of the applied signal. An RC combination in the grid circuit develops this biasing voltage when the signal drives the grid positive with respect to the cathode.

PLATE LIMITER: The stage immediately preceding the discriminator, the plate limiter provides an output having a constant amplitude. A strong input signal is required to swing the limiter plate current between cutoff and saturation, thereby limiting the signal amplitude and providing good noise quieting.

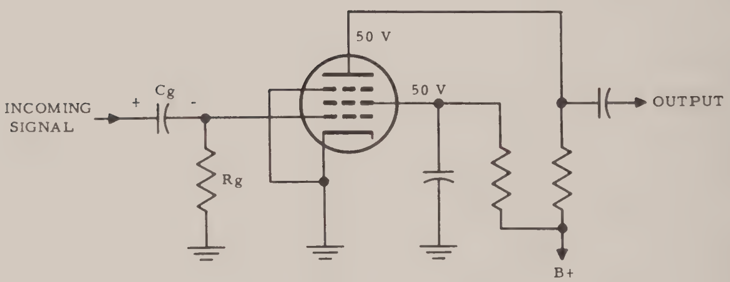
QUIETING: The decrease in noise reproduced by the FM receiver when a signal is received. Receiver quieting is the result of limiter action.

SATURATION: An operating condition of a vacuum tube in which the plate current is a maximum value for the established operating voltages and plate load. Once a tube has reached saturation, the plate current cannot increase further, regardless of signal amplitude.

20-DB QUIETING: A standardized term in two-way communications, this amount of quieting is used in conjunction with the specified receiver sensitivity. Thus, sensitivity may be stated as the minimum signal voltage, at the input terminals of the receiver, required to produce a 20-db reduction (a 10 to 1 voltage ratio) in noise at the receiver output. (See QUIETING.)



LIMITER ACTION
FIGURE 1



LIMITER CIRCUIT
FIGURE 2

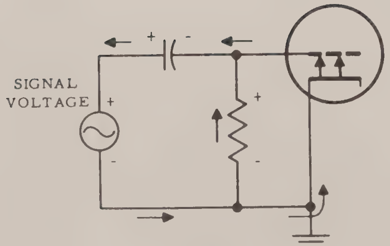


FIGURE 4A

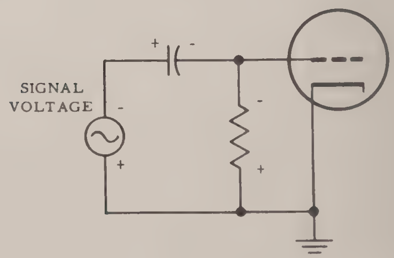


FIGURE 4B

GRID LEAK BIAS

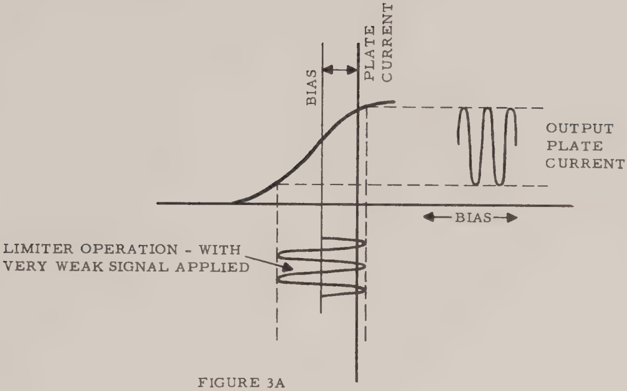


FIGURE 3A

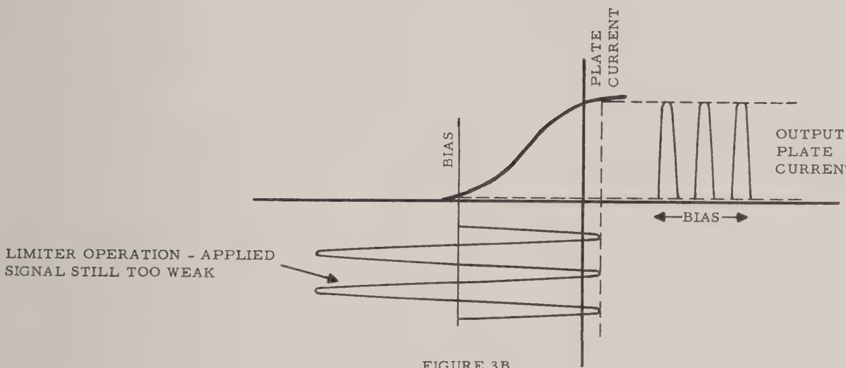


FIGURE 3B

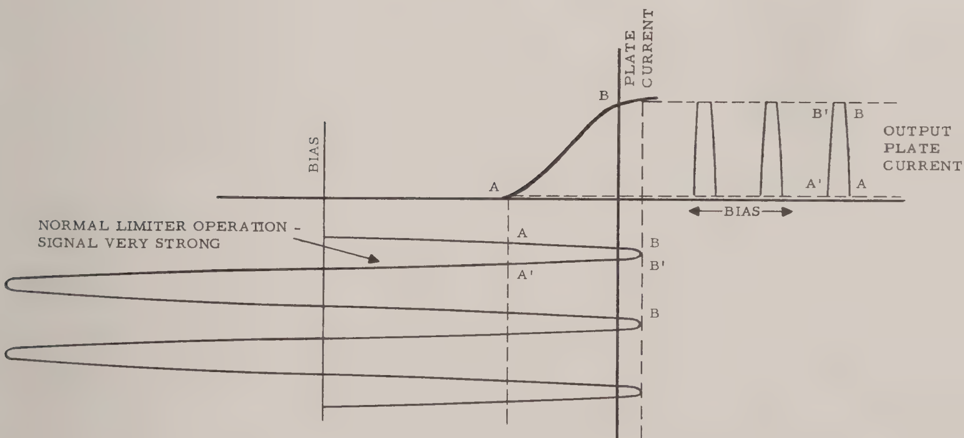


FIGURE 3C

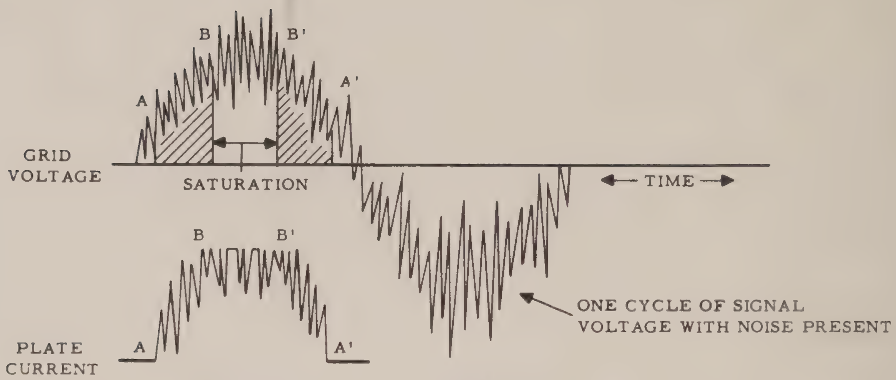


FIGURE 5B FIGURE 5A

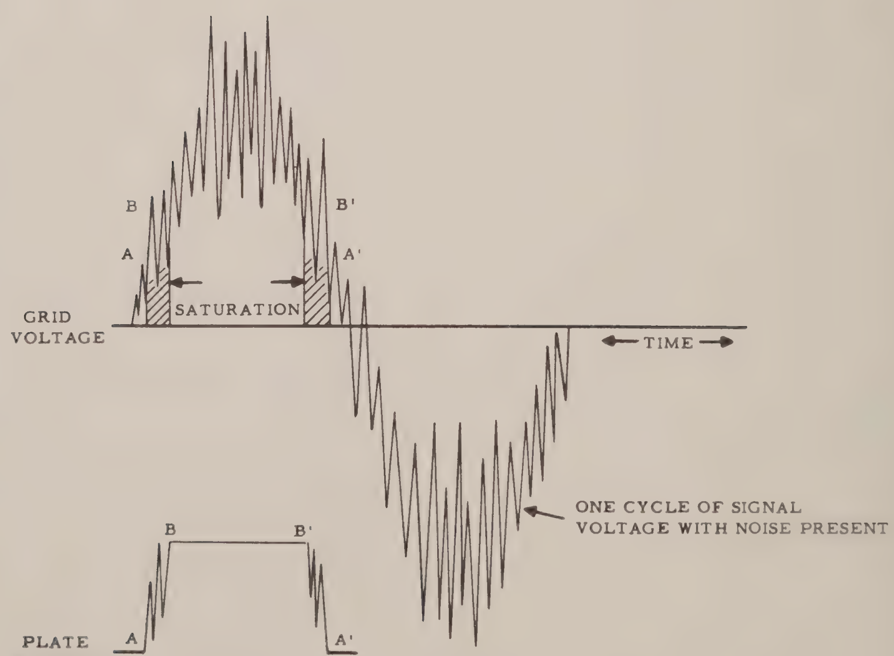
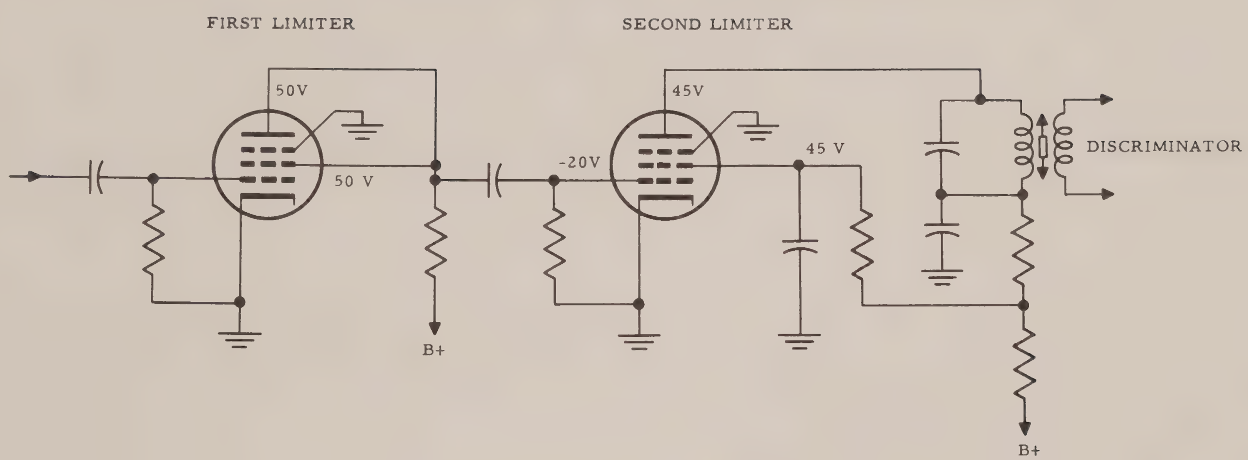
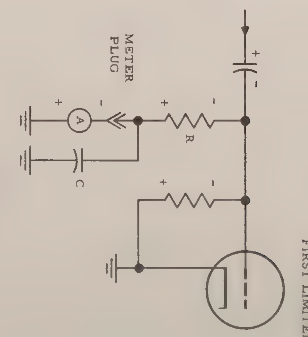


FIGURE 6B FIGURE 6A



TWO STAGE LIMITER

FIGURE 7



LIMITER
METERING
CIRCUIT

FIGURE 8

Motorola Training Institute

4501 West Augusta Blvd., Chicago 51, Ill.

Please PRINT or use STAMP

Name ______________________ Student No. ______

Street ________________ Zone ____ Date ______

City ______________ State _______ Grade ______

EXAMINATION LESSON RA-6

1. The ability of a limiter stage to eliminate amplitude modulation and reduce noise in the FM receiver is dependent upon a strong signal entering the limiter.

   TRUE __________ FALSE __________

2. The plate limiter reduces amplitude variations by: (choose only one answer)

   A. Cutting off the negative half cycle of the signal. A. ______
   B. Cutting off the positive half cycle of the signal. B. ______
   C. Eliminating both the positive and negative peaks. C. ______
   D. Using only the negative portion of the signal. D. ______

3. A receiver has a sensitivity of 1 microvolt. The limiter requires a signal of 3 volts for normal operation. The net gain of the receiver ahead of the limiter should be at least:

   A. 1,000,000. A. ______
   B. 300,000. B. ______
   C. 333,333. C. ______
   D. 3,000,000. D. ______

4. The voltage between the plate and cathode of a limiter stage is usually about __________ to __________ volts.

5. In figure A below, across what component is the bias voltage developed under normal operation? __________ Indicate the polarity of the voltage across this component.

6. For a given limiter circuit the bias is determined mainly by the (amplitude) (frequency) of the signal applied to the grid. Noise voltages (will) (will not) cause bias voltage at the limiter grid.

7. Saturation may be detected by using a meter in the grid circuit of a limiter. The symptom is that ______________________________.

8. For figure A below (limiter), in normal operation (signal being received) the plate current will be (continuous) (a series of pulses). The output signal will have a (constant) (changing) amplitude and will correspond to the (RF) (IF) (audio) frequency.

9. The complete RF waveform in the output of a limiter may be restored by using a __________.

10. The unit of measurement commonly used to indicate the amount of noise reduction by the operation of the limiter is the ______________________.

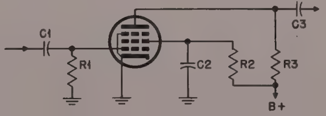


FIGURE A

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-7
FM RECEIVERS

The Discriminator

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-7
FM RECEIVERS

The Discriminator

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

THE DISCRIMINATOR

LESSON RA-7

TABLE OF CONTENTS

NOTICE

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Every day more and more sturdy antenna towers rise into the air, signifying more Two-Way Radio base stations going "on-the-air" for public safety agencies, transportation companies and business and industrial enterprises. Base station antennas for the land-mobile services alone are passing the 100,000 mark.

THE DISCRIMINATOR

Lesson RA-7

Introduction

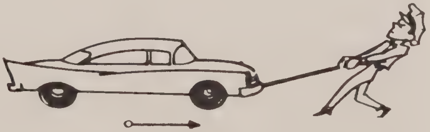
All FM receivers incorporate some circuit device to convert the incoming deviations of the IF signal (which contain the audio message to be reproduced) into voltage variations. The two most popular of these circuits are the discriminator and the ratio detector. The discriminator--which at the present is best suited for the needs of the communications receiver--is the one described in this lesson.

Because the operation of the discriminator depends upon several phase relationships between existing RF voltages, it is often regarded as somewhat more intricate than other circuits found in FM receivers. For this reason it is probably the least understood. Actually, however, these phase relationships can be easily illustrated by means of vectors.

It is not necessary to have a thorough knowledge of vectors for this purpose--a few basic facts are all that is required. All vector information needed in order to analyze discriminator action will be found in the following section entitled "Plain Vector Talk." If you have not had the opportunity to make use of vectors in the past--or if you feel that you are a little "rusty" on the subject--you will find this section helpful before proceeding with the rest of this lesson.

Plain Vector Talk

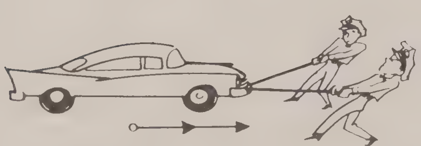
Many of the things that we weigh and measure are described in terms of pounds, feet, or perhaps gallons. Because of their nature, we do not require any further data about these things--the information is complete. Other quantities require that their direction be given before we can make useful application of the information. For instance, an airplane pilot must know the direction of a wind in addition to its velocity. In operating his plane the pilot



SINGLE FORCE

A Vector is an Arrow Pointing in the Direction of some Force. The Length of the Vector Indicates Magnitude.

must take into account the wind direction or he will not fly a straight path to his destination; he may even end up in the wrong place. Or, a person may get in a boat and start rowing to the opposite shore of a river. Unless he takes the river current into account and allows for both its force and its direction, he may find himself downstream from his intended landing spot. Thus, wind and water current must be stated in terms of both magnitude and direction. Many electrical forces, too, must be stated in terms of direction as well as magnitude before we can make intelligent use of them. The vector is a convenient device which can be used to describe both magnitude and direction of forces.



Two Forces Acting in the Same Direction are Shown by "In Phase" Vectors.

A vector is a straight line drawn to a certain length and in a specific direction. In any vector diagram all vectors must have a common starting point, known as the origin. Figure 1A contains two vectors, A and B, drawn from the same origin, "o", but in opposite directions. Furthermore, these vectors have the same length and hence represent forces of equal magnitude. Because they act in opposite directions, these forces oppose each other; because they are equal, they will counteract or cancel each other completely. The resultant of these two forces is zero.

Figure 1B also contains two vectors, A and B, acting in opposite directions. Because the vectors are not the same length they represent unequal forces. The resulting force is determined by the difference in their lengths, and the action will be in the direction of the longer vector, B. If B represents a 300-pound force acting to the right and A is a 100-pound force acting to the left, the net resulting force is 200 pounds to the right.

In figure 1C, the two forces are of unequal magnitude, and they are acting at right angles (90 degrees) to each other. Diagrams like this are commonly used to represent voltages and currents in AC circuits. To analyze the circuit operation it is necessary to determine the combined force which results from these different voltages or currents. This is done as shown in figure 2.

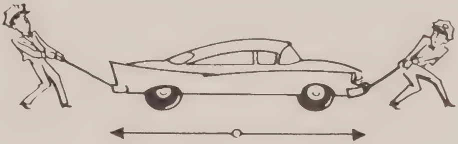
In figure 2A, the two vectors (A and B) are acting at right angles to each other. Their resultant is found by a process known as "completing the parallelogram". From the terminus (end) of vector A, draw a line parallel to vector B. Also draw a line, from the terminus of B, parallel

to A. These lines will cross at a point, AB, which is the terminus of a new vector (A & B), drawn from the origin to the point of intersection. Thus, the resultant of vectors A and B has a magnitude and direction which is determined by the new vector, called AB. If A and B are drawn to a specific scale, the same scale can be used to measure AB; in this manner, the exact magnitude of the final force (A + B) can be found.

In figure 2B, vectors A and B are separated by an angle which is greater than 90 degrees but less than 180 degrees. The parallelogram method is again used to determine the resultant--which is shorter than either of the individual vectors. In figure 2C, the vectors lie in nearly the same direction and their resultant is considerable longer than either of the individual vectors. Again the parallelogram method is used to determine the final force, represented by the resultant vector, AB.

In AC practice, we use the word "phase" to describe the relative directions of separate forces. In figures 1A and 1B the forces oppose each other and are said to be 180° "out of phase." In figures 1C and 2A, the forces are at right angles or 90 degrees "out of phase." The vectors in figure 2C are nearly "in phase."

The system shown in figure 3A provides an accurate method which is used to describe the phase of vectors. Two lines are drawn at right angles to each other--the horizontal line is called the X axis and the vertical line is the Y axis. The entire system contains 360 degrees, and since the two axes are at right angles to each other, there will be 90 degrees in each section (quadrant). The quadrants are numbered as shown, and all vectors are considered in relation to the "zero reference," which is that portion of the X axis which lies to the right of Y.



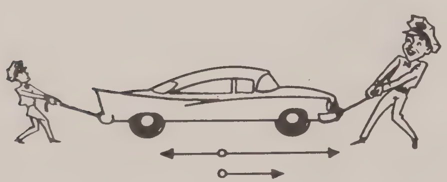
EQUAL FORCES OUT OF PHASE

Vectors of the Same Length and Pointing in Opposite Directions Indicate Two Opposing Forces of Equal Magnitude. The Resultant Force is Zero.

Vectors are thought of as being in constant rotation, moving counterclockwise. It is permissible, however, to "stop" the vectors at any instant to consider their phase angles and analyze what is happening in the circuit. Vectors A and B at figure 3A are in the first quadrant and they are both "leading" the zero reference. A is leading by 20 degrees and B is leading by 60 degrees. With reference to each other, A is lagging B by 40 degrees and B is leading A by 40 degrees. Vector A is said to be at its 20 degree phase; vector B, at its 60 degree phase. Thus, phase refers to the degree of rotation from the refer-

ence (zero degrees). The phase difference between A and B is 40 degrees. Sometimes we say that these vectors are "displaced" by 40 degrees.

In figure 3B, vectors A and B are not in the same quadrant, and B is now said to be lagging A by 90 degrees (or leading A by 270 degrees). Also, as vectors represent AC quantities which are not only continually changing in amplitude, but also periodically changing direction, we designate all vectors as being positive whenever they are above the X axis, and negative whenever they are below the X axis. In figure 3B, vector A is positive; vector B is negative.



RESULTANT UNEQUAL OUT OF PHASE FORCES

Unequal but "Out of Phase" Forces Result in a Final, Smaller Force.

Vectors can thus be used to represent voltages and currents in an AC circuit. The length of the vector represents the magnitude of the voltage or current, the position of the vector (above or below the X axis) indicates polarity, and the relative directions of the vectors show their phase relationships. When arranged as shown in figure 3, the vectors indicate which voltage or current is leading and which is lagging, and the parallelogram method can be used to determine the resulting value at any instant.

This brief discussion of vectors has been necessarily confined to elementary principles.[1] A knowledge of these principles, however, will make it easier to understand the various phase relationships between voltages which are present in the discriminator circuit. The basic action of this circuit will now be discussed.

Basic Discriminator Action

Before we attempt to analyze the phase relationships between voltages in the discriminator, we should know what happens when certain relationships occur. Let us start, then, by assuming that certain phase relationships take place, and see how the discriminator circuit functions with these assumed voltages.

The simplified discriminator circuit of figure 4 is similar in operation to the FM detector described in lesson 1. The two coil sections, L_1 and L_2, together constitute the secondary of a discriminator transformer tuned to the center frequency of the incoming signal. Coil L_3 is common to both diode circuits. The upper diode, D_1, rectifies the RF voltage applied to or developed across coils L_1 and L_3. The lower diode, D_2, rectifies the RF voltages developed across L_2 and L_3. The

1. See TM 11-681 Electrical Fundamentals, pages 185-189; also FM Transmission and Reception, by Rider and Uslan, pages 407-411.

voltages across R_1 and R_2, resulting from the rectified diode currents, will then be determined by the total or effective voltage applied to each diode, respectively. A steady DC voltage is maintained across each resistor by means of two capacitors (not shown in the diagram), which are connected across the two resistors.

The arrows in figure 4 indicate the direction of the diode currents. The resulting voltages across the resistors will have polarities as shown. The value of the voltage across each resistor depends upon the current, which, in turn, is determined by the applied signal. The total voltage at each diode, however, is not just the arithmetical sum of the voltages across the separate coils; there is a phase difference between these coil voltages. The effective voltage thus depends not only upon the magnitude of the separate voltages, but also upon their phase relationship.

Figure 5A shows the phase relationship of the voltages appearing across the three coils when the incoming signal is at its center frequency. The voltages across L_1 and L_2 are equal in magnitude, for they are developed across the two halves of a transformer winding tapped at its electrical center. The voltage across L_1 is leading the voltage across L_3 by 90 degrees, and the voltage across L_2 is lagging the voltage across L_3, also by 90 degrees. With these phase relationships existing between the voltages, and with the voltage across L_1 equal to that across L_2, the resulting vectors for the voltages of D_1 and D_2 will also be equal in length, as shown in figure 5A.

The discriminator output is a combination of the voltages appearing across resistors R1 and R2, which are connected in series with each other, insofar as the output voltage is concerned. With equal voltages applied to the two diodes and with equal values of resistance for R1 and R2, the resulting voltages across these resistors must also be equal. As far as the output terminals are concerned, however, the voltages across the resistors have opposing polarities and the net voltage is zero.

This condition is illustrated in figure 6A, where the two resistors of figure 4 have been redrawn to show the output when the signal is at its center frequency (no deviation). A voltmeter would read 5 volts when connected across either resistor, but if the meter were connected across the output terminals it would read zero. (Each test lead of the meter would be at the same potential, and voltage is the difference of potential.) This condition exists because of the 90-degree phase relationship between the voltage of coil L3 and the voltages of L1 and L2. Thus, when the incoming signal is at the center frequency (no deviation), the effective voltages operative in each section of the discriminator are equal and the output is zero.

Figure 5B shows the phase relationship when the deviation of the incoming signal is above center frequency (positive deviation). The voltage E_{L3} is again the reference voltage, for it is common to both circuits. The voltage of E_{L1} is now less than 90 degrees out of phase with E_{L3}, and the voltage E_{L2} is more than 90 degrees out of phase with E_{L3}. Because the voltage vectors E_{L1} and E_{L3} are more "in phase," their resultant voltage increases even though the individual voltages of E_{L1} and E_{L3} remain the same. Thus, the applied voltage to diode D1 increases and we may expect a higher current (and voltage) for R1. The voltage resulting for E_{L2} and E_{L3} decreases at the same time, for these voltages are now more "out of phase." The applied voltage to diode D2 decreases, and the voltage for R2 must also decrease. In figure 6B, it is assumed that the voltage of R1 has increases to 6 volts while that of R2 has decreases to 4 volts. The difference between these two voltages is now 2 volts, and the upper output terminal is positive. Thus, whenever the incoming signal deviates above center frequency the output of the discriminator becomes positive.

Figure 5C shows the phase relationship when the deviation of the incoming RF is below center frequency (negative deviation). The phase relation of the circuit voltages changes again, but in this instance the shift is in the opposite direction. The voltages E_{L2} and E_{L3} are more in phase while those of E_{L1} and E_{L3} are more out of phase. The effective voltage applied to D1 is less, while that applied to D2 increases. The voltage increases across R2, and in figure 6C we have assumed that it is now 6 volts, while the voltage of R1 is 4 volts. The difference is again 2 volts at the output terminals, but the upper terminal is now negative (less positive) with respect to the ground terminal, so the output voltage is negative. From this action we see that an incoming signal below the center frequency produces a negative discriminator output.

Let us summarize at this point. At the center frequency (resonance), the voltages across R1 and R2 are equal, resulting in zero output voltage from the discriminator. Furthermore, in order to have either a positive or negative voltage at the output, the voltages of R1 and R2 must be unbalanced, and this results from an unbalance in the effective RF voltages which are applied to the two diode rectifiers. Four basic ideas are involved: 1. The discriminator converts the incoming frequency variations into voltage changes. 2. The center frequency (no deviation) produces zero output. 3. Frequency deviations above center cause a positive voltage output. 4. Frequency deviations below center cause a negative voltage output.[2]

Deviation and the Discriminator Output

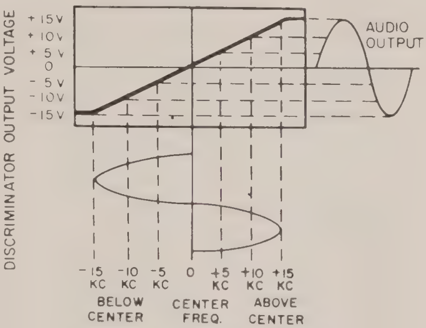
Out next consideration concerns the amplitude and frequency of the

2. See TM 11-668 FM Transmitters and Receivers, pages 158-160; also FM Transmission and Reception, by Rider and Uslan, pages 292-300.

output voltage produced by the discriminator. At the FM transmitter, (1) the audio amplitude controls the amount of deviation, and (2) the audio frequency determines the rate of deviation. For the output voltage from the discriminator to correspond to the audio message we want to hear, the process which is taking place at the transmitter must be reversed. At the receiver, then, the discriminator must operate so that (1) the amount of frequency deviation from center will control the amount of output voltage, and (2) the rate of deviation will determine the frequency.

First, let us see how the amount of frequency deviation from center controls the amount of output voltage. When the incoming signal deviates from the center frequency, the voltages of L1 and L2 shift in phase, producing higher and lower voltages respectively, at the diodes. The greater this phase shift becomes, the more these voltages (E_{L1} and E_{L2}) are in-phase and out-of-phase respectively, with E_{L3}. The phase shift of the secondary voltages, E_{L1} and E_{L2}, is determined by the amount of deviation of the incoming signal from center frequency. Thus, the amount of voltage produced at the output of the discriminator is determined by the amount of deviation of the incoming FM signal.

Now let us see how the rate of deviation determines the frequency of the audio output voltage. Each time the incoming signal deviates above and below center, the output voltage must change polarity. Because each complete deviation of the carrier produces one complete voltage change in the discriminator output, the frequency of the output voltage must correspond to the rate, or number of deviations of the incoming signal.



A Typical Wide-Band Discriminator Response Curve. Only a ± 15 KC Deviation Produces Full Output Voltage.

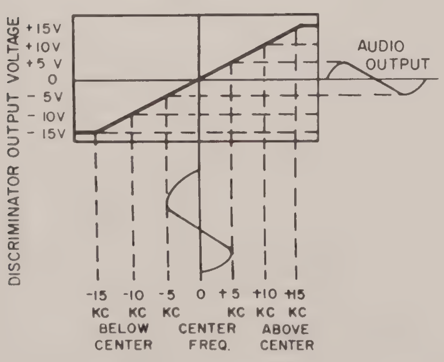
Discriminator Phase Relationships

In the foregoing analysis of discriminator operation we assumed certain phase relationships for the circuit voltages. It remains to be seen how these phase relationships take place.

The circuit of figure 7 is that of a conventional "Foster-Seeley" discriminator. The components of figure 7 correspond to those of figure 4 and the circuit operation will be the same as in figure 4. The plate circuit of the last limiter is tuned to the IF center frequency, and coil L1-L2 is tuned to the same frequency by means of C5. C1 and C2 are RF filter capacitors and maintain the voltages across R1 and R2 at a steady

DC value. The combination of R3, R4, and C3 make up the external load on the diodes, and the rectified current of both diodes passes through R3 and R4, so that these resistors become a common load for both diodes.

In order to illustrate the phase relationships of the RF voltages, the circuit of figure 7 has been simplified to that of figure 8. Because capacitors C1 and C2 act like a short to RF (at the IF frequency), the cathodes of both diodes are at RF ground potential. Also, as far as C4 is concerned, the primary is connected directly to the center-tap of the secondary winding. Thus, for an analysis of the RF portion of the discriminator, we can study figure 8.



± 5 KC Deviation Produces a Small Output Voltage in a ± 15 KC Deviation System.

To construct the vector diagram of figure 9A, we must first establish a reference voltage. The voltage developed across the plate tank circuit (LP and CP) of the limiter is most convenient for this purpose, and this voltage (Ep) is shown as a vector along the X axis, to the left. All voltages in figure 9 will be considered with respect to this primary voltage, Ep.

The tank circuit in the limiter plate (LP and CP) and the coil (L3) are in series with each other, and connected between B plus and B minus. The voltage across L3 decreases as the voltage across the tank (Lp) increases. These two voltages are therefore 180 degrees out of phase with each other, and the voltage across L3 is shown as a vector(E_{L3}) along the X axis, to the right.

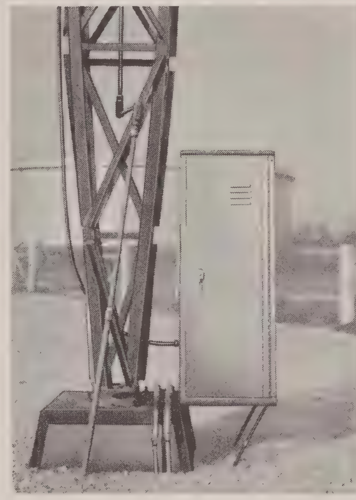
We must also consider the voltage which is induced in the transformer secondary winding (L1, L2) as a result of mutual coupling. This voltage (E_{ind}) is thought of as being "applied" to the secondary tuned circuit. It is always 180 degrees out of phase with the primary voltage (Ep), so it is drawn to the right along the X axis, coinciding in phase with E_{L3}. This induced voltage (E_{ind}) causes a circulating current (Is) in the secondary tank, and, at resonance, this current is in phase with the applied voltage. Since it is in phase with E_{ind} and E_{L3}, this current (Is) is also drawn to the right on the X axis.

The current in the secondary (Is) produces voltages across L1 and L2 which are 180 degrees out of phase with each other and 90 degrees out of phase with the current, Is. In a conventionally-wound discriminator transformer,

the voltages thus produced will be as shown in figure 9A, with the voltage of L1 leading the voltage of L3, and the voltage of L2 lagging the voltage of L3, each by 90 degrees.

The voltage applied to diode D1 is the combined voltages across L1 and L3, while the voltage applied to diode D2 is the combined voltages across L2 and L3. The resultant diode voltages will then be as shown by the vectors E_{D1} and E_{D2}. These vectors are the same as those of figure 5A, which were the vectors previously assumed in explaining the operation of the discriminator.

Our discussion of phase relationships up to this point has been concerned with resonant conditions only. When the incoming signal is not at resonance, the phase relationships of the voltages is represented vectorially as shown in figures 9B and 9C. Three of the voltages (Ep, E_{ind}, and E_{L3}) maintain the same phase relationship whether the incoming signal is at resonance or not. Moreover, the vectors E_{L1} and E_{L2} are always drawn at 90 degrees out of phase with the current vector, Is, since these voltages are always 90 degrees out of phase with this current through L1 and L2. With the secondary no longer at resonance, however, the secondary current (Is) is no longer in phase with the applied voltage (E_{ind}). This out-of-phase current in the secondary causes equal out-of-phase voltages across L1 and L2, and when these voltages (E_{L1} and E_{L2}) combine with E_{L3}, they cause unequal diode voltages, E_{D1} and E_{D2}.



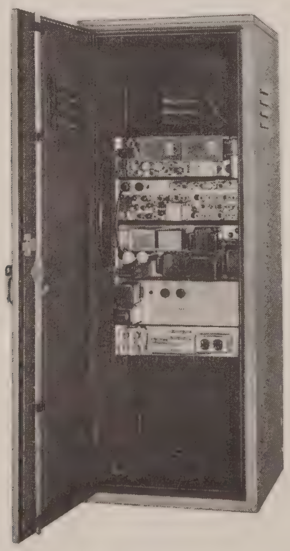
A Typical Outdoor Base Station Installation. This is an All-Weather Type of Cabinet.

Figure 9B (like figure 5B) shows the phase relationship when the incoming RF deviates above resonance. In the secondary tuned-circuit, the inductive reactance exceeds the capacitive reactance, and the circuit becomes inductive. In an inductive tank circuit, the circulating current lags the applied voltage and, in figure 9B, the current vector (Is) must be drawn lagging the voltage (E_{ind}), as shown.

Figure 9C (like figure 5C) shows the phase relationship when the deviation of the incoming RF is below resonance. The capacitive reactance now exceeds the inductive reactance, and the secondary

circuit becomes capacitive. In a capacitive tank circuit, the circulating current leads the applied voltage and, in figure 9C, the current vector must be drawn leading the voltage.

It can now be seen how the amount of deviation, by establishing the in-phase and out-of-phase condition of the secondary voltages (E_{L1} and E_{L2}), determines the amount of output. When the incoming signal is far from center frequency, the secondary circuit becomes highly reactive (either inductive or capacitive), and the secondary current, now considerably out of phase with the induced secondary voltage (E_{ind}), sets up equally out-of-phase voltages across L1 and L2. These voltages (E_{L1} and E_{L2}), combining with the voltage across L3, causes unequal voltages to appear at the diodes, resulting in a large positive or negative output.[3]



Here We See the Inside of an All-Weather Base Station Cabinet.

Review

At this point in the lesson it might be well to review what we have already learned about the discriminator.

1. The discriminator is a double-diode rectifier arrangement in which the diode output voltages, as produced across the load resistors, are combined to make up the discriminator output.

2. At resonance the discriminator output is zero. Signals above center frequency cause a positive voltage while signals below center cause a negative output.

3. Two separate signal voltages, present in each diode, produce a resultant voltage at each diode. At resonance these diode voltages are equal and the output is zero. Above or below resonance the diode voltages become unbalanced and the output is either positive or negative.

4. The unbalance of the diode voltages is due to changing phase relationships between the RF voltages and this phase shifting is caused by the applied signal being out of resonance with the tuned secondary. The secondary current, no longer in phase with the induced secondary voltage, causes a corresponding phase shift of voltages (E_{L1} and E_{L2}).

3. See TM 11-668 FM Transmitters and Receivers, pages 93-94; also FM Transmission and Reception, by Rider and Uslan, pages 301-308.

5. For proper discriminator action the primary and secondary of the transformer must be tuned to resonance at the center frequency of the applied signal.

Modified Motorola Phase Detector

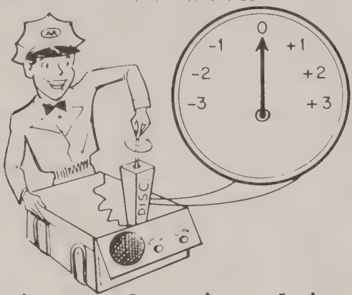
The Foster-Seeley discriminator circuit which has been described here makes use of the changing phase relationship of the voltages existing in the primary and secondary tuned circuits of a transformer. This description will be of help in analyzing the operation of any discriminator circuit employing these principles. Such circuits are called "phase detectors" and most FM detectors rely upon this principle although in many cases the arrangement may appear to be quite different from that of figure 7.

A Motorola circuit, found in many present-day receivers, is shown in figure 10. The circuitry is that of a modified Foster-Seeley or phase detector. The basic operation is the same as that of figure 7, but there are several distinguishing features which warrant consideration.

We found, in figure 7, that two separate voltages appear in the secondary as a result of voltage developed in the primary. One secondary voltage is produced by the mutual magnetic coupling between the primary and secondary windings of the transformer. The other voltage is due to the direct coupling (C4) from the primary to the secondary. Figure 10 also has two voltages in the secondary. The first voltage is identical to that of figure 7--there is mutual inductive coupling in the transformer. The second voltage is also due to a direct coupling between the circuits, only in figure 10 the connection is not to a center-tap at the secondary coil. Instead, this tap is made at the midpoint of two series capacitors, connected in parallel with the secondary winding. The electrical action is the same; the center of the coil must be at the same potential as the center of the two capacitors. An important advantage of this method of coupling is that it is easier to tap the electrical center of the secondary circuit. This is particularly true when the coil is the tuning element. Tuning is then accomplished by changing the position of an iron core in the coil; this changes the balance of the two halves of the winding in a center-tapped coil. The overall effect of this method of capacitance coupling is that an equal voltage is applied to each diode circuit regardless of the position of the tuning core.

The remainder of the circuit operates in the same manner as the circuit of figure 7. The combination of R3, R4, and C3 make up the external load on the diodes and the current path is completed through R1 (for D1) and R2 (for D2). The rectified current of both diodes passes through the load resistors, R3 and R4, so that these two resistors become a common load for the diodes. The

diode currents pass through R3 and R4 in opposite directions, however, so the resulting current and voltage will always be determined by the difference of these current.



When the Secondary of the Discriminator Transformer is Tuned to the Center Frequency of the Incoming Signal, the Discriminator Output Voltage is "Zero."

When tuning the discriminator, two meter positions are used; these are marked 4 and 5, respectively. (The reason for the position numbers will be evident after studying the lesson on metering.) The meter at position 4 is used to measure the output of the discriminator circuit when adjusting the secondary to resonance at the center frequency--at resonance the output reading is zero. With the meter connected at position 5, the primary of the discriminator transformer is adjusted for a maximum reading. The two diodes are now in parallel and the meter indicates the amount of voltage being applied from the primary. In the actual tuning procedure, the secondary coil terminals are shorted so that the reading is due to the primary tuning rather than to the setting of the secondary circuit.

Deemphasis at the Discriminator

Before we can discuss intelligently the "deemphasis" at the discriminator output, we must first know why it is required. At the transmitter, a system called "preemphasis" is used to improve the signal-to-noise ratio of the upper voice frequencies. This is accomplished by making the higher voice frequencies produce a greater amount of deviation than normal.

Because of this preemphasis at the transmitter, the receiver must include a reverse process (called deemphasis) in order that the reproduced message will sound normal. The combination of preemphasis (at the transmitter) and deemphasis (at the receiver) provides a more uniform signal-to-noise ratio for the complete speech range--from 300 to 3000 cps, generally, for two-way mobile applications. The amount of preemphasis introduced at the transmitter is normally 6 db per octave; since 6 db is equivalent to a voltage ratio of 2 to 1, this means that each time the audio frequency is doubled, the voltage ratio (or deviation increase) is also doubled.

The deemphasis circuit in figure 10 is made up of R3 and C3, with the corrected audio voltage appearing across the capacitor. The reactance of a capacitor varies inversely with frequency, so higher frequency audio signals will have a lower voltage at the output than will the lower frequencies. The values are selected so

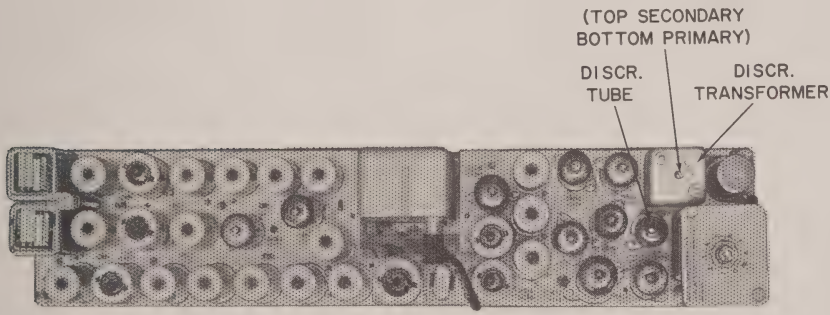
that the amount of deemphasis at the receiver corresponds to the amount of preemphasis introduced at the transmitter, 6 db per octave. Thus, the message sounds natural. The potentiometer in parallel with capacitor C3 becomes the volume control for the receiver, for it provides a means of selecting the desired amount of audio voltage which is applied to the following audio section[4].

Motorola Capacitance Discriminator

Motorola has developed and patented a "Capacitance Discriminator" which is used extensively in two-way and other FM equipment. This discriminator operates as a phase detector, and the principle of operation is very similar to that of the Foster-Seeley circuit.

The capacitance discriminator, shown in figure 11A, derives its name from the manner in which the RF voltage is applied to the secondary tank circuit--this is its distinguishing feature. While the Foster-Seeley uses a conventional double-tuned transformer in which the secondary voltage is due to mutual inductive-coupling between the windings, the Motorola circuit avoids inductive-coupling by enclosing the primary and secondary coils in separate cans or shields. The voltage in the secondary tank circuit is produced by establishing a capacitance bridge which is purposely unbalanced in order to develop the desired amount of RF.

The "bridge" of figure 11A has been redrawn in figure 11B for the purpose of this analysis. Points 1 and 2 of figure 11B correspond to points 1 and 2 of figure 11A, and the secondary coil, L, as well as the two capacitors, C1 and C2, are the same in both figures. The capacitance identified as C6 in figure 11B repre-

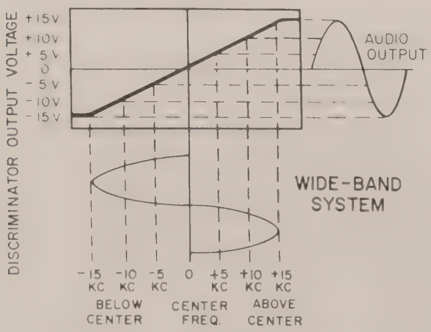


This Photo Shows the Location of the Discriminator Components of a Typical Motorola Receiver.

4. See TM 11-668 FM Transmitters and Receivers, pages 27-29; also FM Transmission and Reception, by Rider and Uslan, pages 170-174.

sents the total capacitance between point 2 and ground, which includes the circuit wiring as well as the internal capacitance of the diode, D2, and capacitor C4. The capacitance shown as C7 in figure 11B cannot be identified as a separate component in figure 11A, but this represents the total capacitance of the circuit, between point 1 and ground. The bridge is balanced whenever the ratio of C2 to C1 is the same as the ratio of C6 to C7, or whenever the ratio of C2 to C6 is the same as the ratio of C1 to C7. When the bridge is balanced, there can be no voltage across the coil, L, and with no voltage to initiate a circulating current through the tuned secondary, composed of L, C1 and C2, there will be no discriminator action.

To establish an RF voltage across the secondary coil, L, the bridge must be unbalanced. This can be done by changing the value of any one of the bridge elements--C1, C2, C6, or C7. The values



The Wide Band Discriminator Produces About 15 Volts of Audio Output when the Deviation is ± 15 KC.

of the bridge are so chosen that there is a definite unbalance of the RF at the opposite ends of the coil. (In figure 10A, this unbalance is realized by the large capacitance of C4.) The resulting voltage applied to the coil sets up a circulating resonant current in the circuit in much the same manner as the voltage induced in the secondary winding of the basic circuit of figure 7. By proper selection of the capacitance of each portion of the bridge, the amount of voltage at the secondary coil may be controlled. The greater the unbalance, the greater the voltage applied to the coil and the greater the secondary current. The RF voltage applied to the secondary largely determines the amount of recovered audio voltage at the discriminator and for this reason it is important that the proper amount of unbalance in the bridge be maintained. (This is particularly important to keep in mind when one of these capacitors is defective and must be replaced. The replacement capacitor must have the same characteristics as the original.)

Two RF voltages are operative in each diode circuit. One voltage is present across D1 and D2 by virtue of the bridge being placed in parallel to the primary, and a portion of this voltage will be applied to the C6 and C7 sections of the bridge. The second voltage is the result of the circulating tank current through the tuned circuit composed of L, C1, and C2. Because of the common ground return of C6 and C7, the center of the coil is effectively

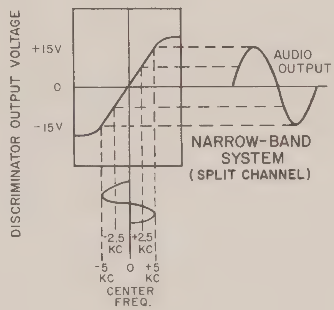
at ground potential as far as RF is concerned. One half of the RF voltage developed across the coil is applied to D1 and the other half is applied to D2. These voltages combine to produce the effective RF at each diode, and at center frequency these voltages have the same value, resulting in zero output from the discriminator. When the signal deviates from center frequency the phase change which takes place between the RF voltages is the same as in the basic discriminator.

The output circuit arrangement of the capacitance discriminator is similar to that of figure 10. The load consists of resistors R3 and R4, with C3 and R3 performing the deemphasis operation. The current through diode D1 completes its path through R1 and the load, while the D2 current path is completed through R2 and the load. Both diode currents pass through the load resistors, but in opposite directions, so that the resulting output voltage is determined by the difference of the rectified currents.

The two meter positions, 4 and 5, provide for adjusting the primary and secondary tuned circuits for resonance at the center frequency of the incoming signal. The procedure is the same as in figure 10. Meter position 5 is used in tuning the primary; meter position 4 is used to adjust the secondary.

Discriminator Response Curve

A discriminator response curve shows the amount of output voltage from the discriminator for specified amounts of deviation. The curve also shows how much deviation is accepted without distortion, and how much the discriminator can drift from center frequency before distortion occurs. Figure 12 shows such a curve.



If the Output Voltage of the Narrow-Band Discriminator is to be the Same as that of the Wide-Band Unit, the Response Curve must have a Relatively Steep "Slope."

The amount of deviation above and below center frequency is plotted horizontally and the output voltage is plotted vertically. From the graph, deviations of 10, 20, and 30 kc produce outputs of 10, 20, and 30 volts respectively. This applies to deviations both above and below center--deviations below center cause a negative output voltage, and deviations above center provide a positive output voltage. At the center frequency (no deviation) the output voltage is zero.

The frequency of the incoming signal is not always at the exact center. Moreover, the tuned secondary of the discriminator transformer may change frequency

slightly with changes of temperature. This does not mean that the output is distorted, however, for the response curve is linear for a greater deviation than that of the signal. The discriminator response curve of figure 12 is linear over a deviation of plus and minus 30 kc. while the system in which this discriminator is used employs a deviation of plus and minus 15 kc. Thus, if the discriminator secondary is not at exact center frequency, or if the incoming IF signal is not at the exact frequency for which it was designed, the signal will still operate over a linear portion of the curve and the output voltage is not distorted by the discriminator.

The amount of output voltage depends upon the design of the transformer and circuit values. In narrow band-width systems, the discriminator is designed so that the smaller deviations produce comparatively high output voltages. Thus, for a system operating under a plus and minus 5-kc deviation, the discriminator curve should show as much output voltage at ± 5 kc as is produced by a deviation of 15 kc in figure 12.

Summary

Phase discriminators (including the Motorola Capacitance Discriminator explained in this lesson) depend upon the phase relationships of RF voltages applied to two diodes. Incoming frequency deviations cause the RF voltages to change phase and produce a varying voltage output.

The discriminator output is zero when the center frequency is applied, but the output is either positive or negative when the signal swings above or below center.

The phase shift caused by an off-resonant signal produces a stronger signal at one diode than at the other. Under these conditions, the output is no longer balanced and a positive or negative output voltage results. The amount of output voltage depends upon the amount of deviation of the incoming signal from center frequency.

In the basic circuit, the secondary voltage is a result of mutual induction coupling between two transformer windings. The Motorola Capacitance Discriminator, instead of magnetic coupling, makes use of capacitive coupling to the secondary as provided by an unbalanced capacitance-bridge circuit.

FM systems use preemphasis to improve the signal-to-noise ratio of the higher voice frequencies. To restore the discriminator output to normal, a deemphasis network is required. To have proper balance between the audio frequencies, the amount of deemphasis at the receiver must correspond to the preemphasis introduced at the transmitter.

IMPORTANT WORDS USED IN THIS LESSON

DEEMPHASIS: Because of the preemphasis introduced at the transmitter, the FM receiver must include a deemphasis circuit in order to restore its audio output to a normal balance between the high and low frequencies.

DISCRIMINATOR: A type of FM detector which recovers the audio component from the deviations of the applied FM signal. Most communications use some form of the discriminator circuit.

PHASE: As used in AC, phase refers to any instantaneous time within the AC cycle. Because time is usually measured in the degree of angular rotation, phase is designated in degrees, as 45° phase, etc.

PHASE DETECTOR: An FM demodulator or detector, its operating depending upon a changing phase relationship between the operating voltages within the circuit. As the incoming signal deviates from center frequency, these voltages change in phase to accomplish the required detection.

PHASE DIFFERENCE, PHASE ANGLE, or PHASE DISPLACEMENT: A comparison of the instantaneous phases of two AC voltages or currents. If at some specific time, one voltage is at its 90° phase and another is at its 60° phase, the phase difference, phase angle, or phase displacement is then 30°.

PREEMPHASIS: A system of emphasizing the higher modulating frequencies at the FM transmitter, by allowing a higher than normal deviation for those higher frequencies. This results in an improved signal-to-noise ratio for the upper frequencies.

STUDENT NOTES

STUDENT NOTES

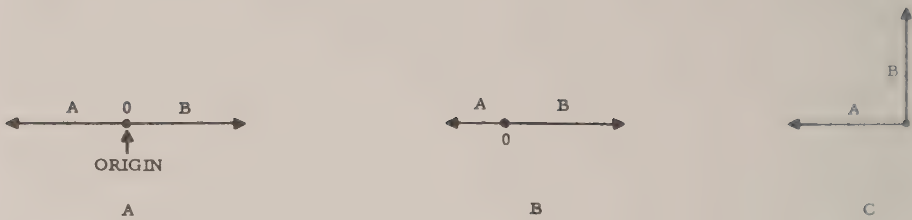


FIGURE 1.

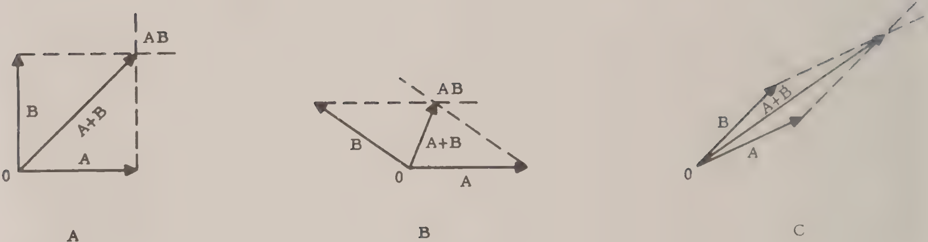


FIGURE 2.

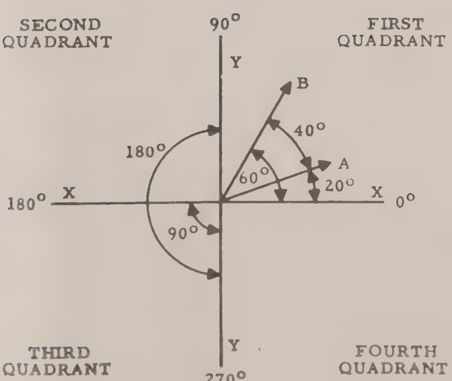


FIGURE 3A

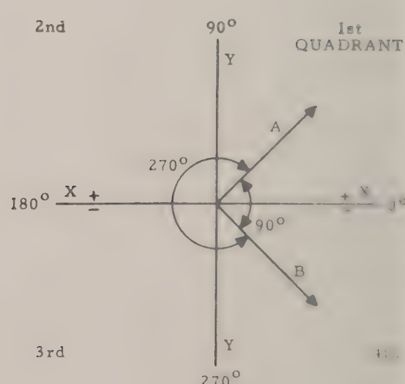
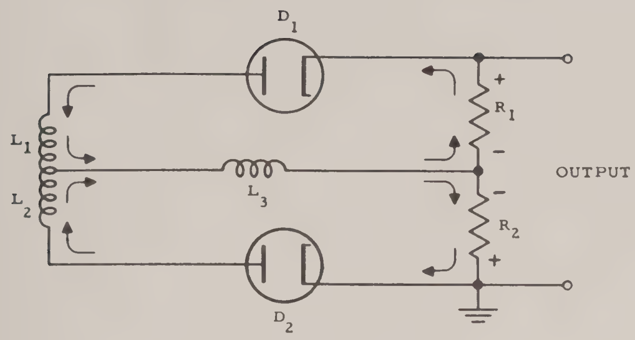
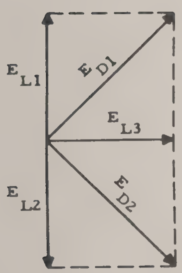


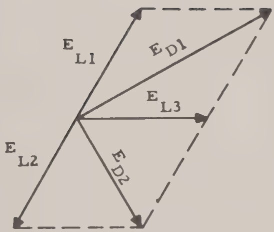
FIGURE 3B



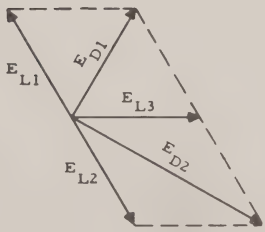
THE DISCRIMINATOR
FIGURE 4



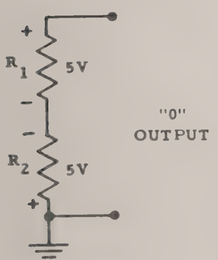
NO DEVIATION
FIGURE 5A



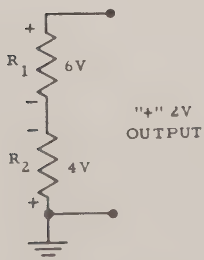
"+" DEVIATION
FIGURE 5B



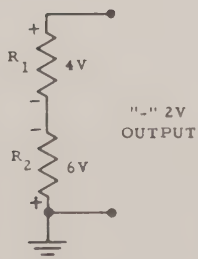
"–" DEVIATION
FIGURE 5C



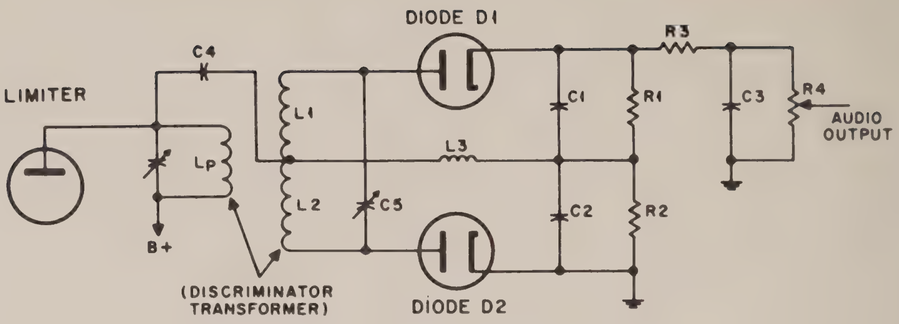
NO DEVIATION
FIGURE 6A



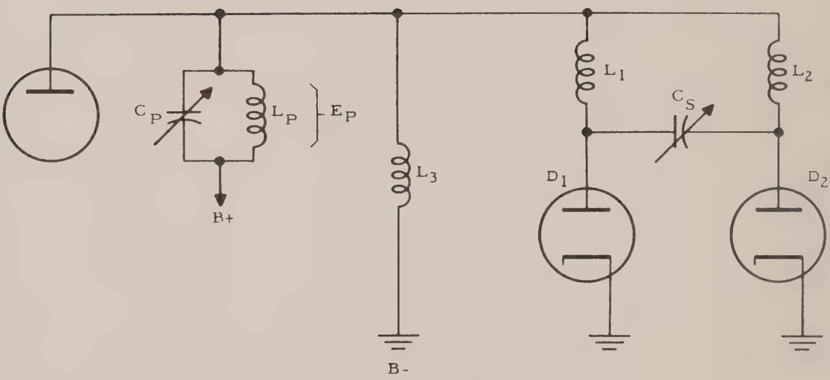
"+" DEVIATION
FIGURE 6B



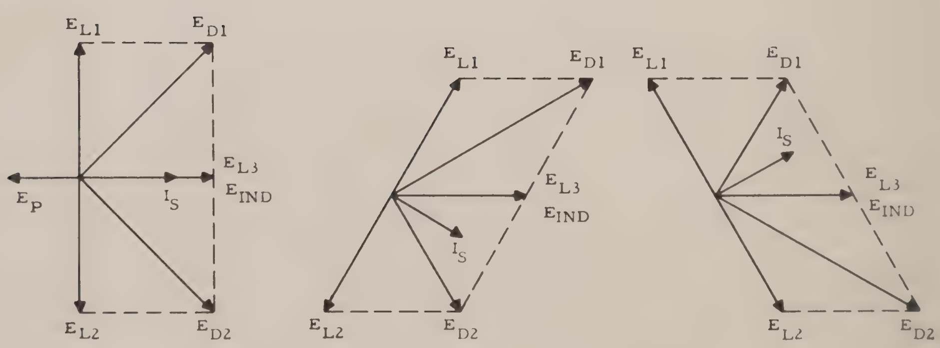
"–" DEVIATION
FIGURE 6C



CONVENTIONAL DISCRIMINATOR
FIGURE 7



SIMPLIFIED RF CIRCUIT OF FIGURE 7
FIGURE 8



AT RESONANCE
FIGURE 9A

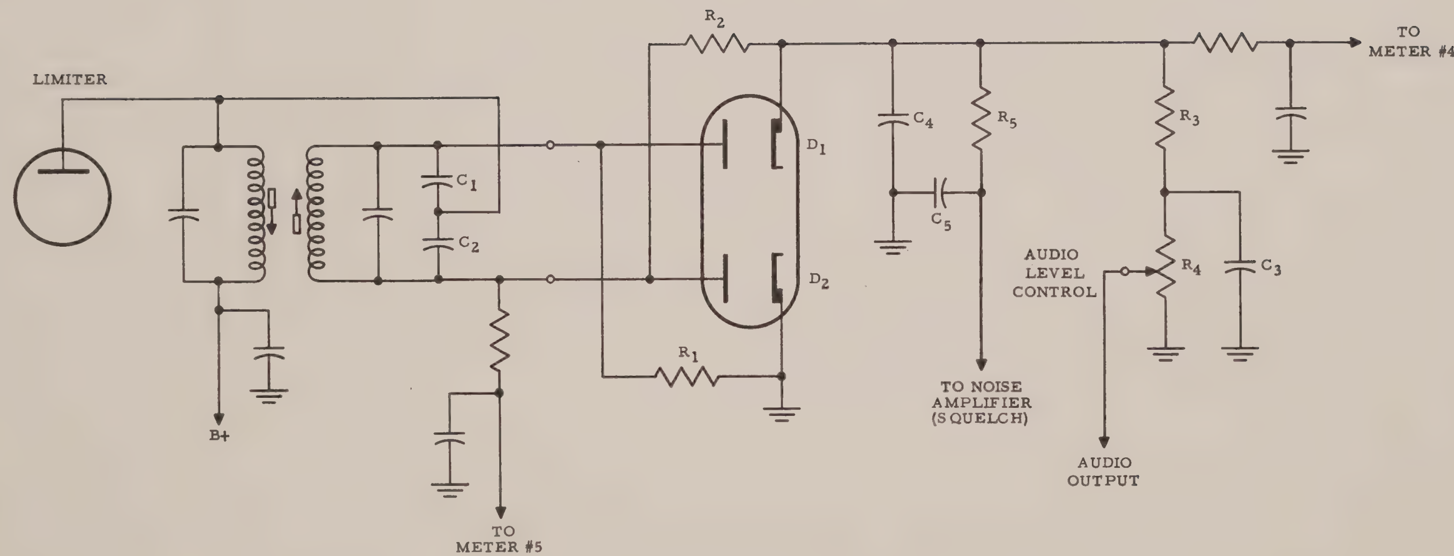
ABOVE RESONANCE
FIGURE 9B

BELOW RESONANCE
FIGURE 9C

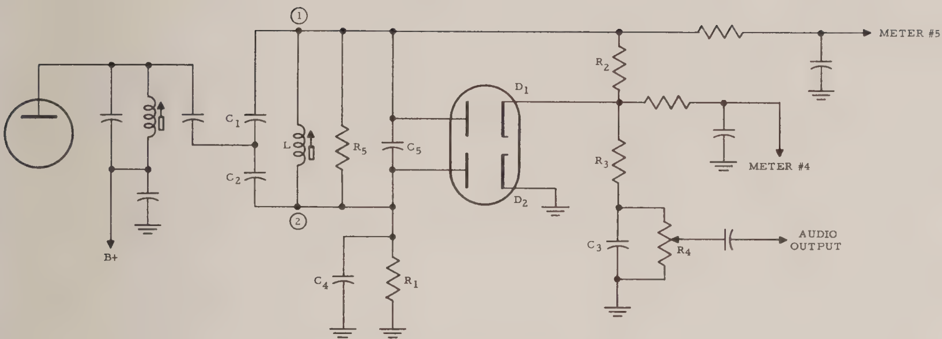
PHASE RELATIONSHIPS IN DISCRIMINATOR

STUDENT NOTES

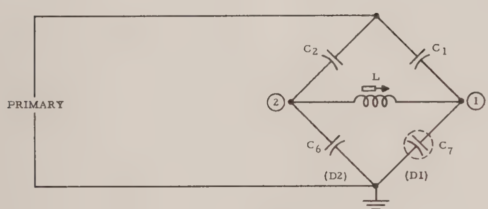
STUDENT NOTES



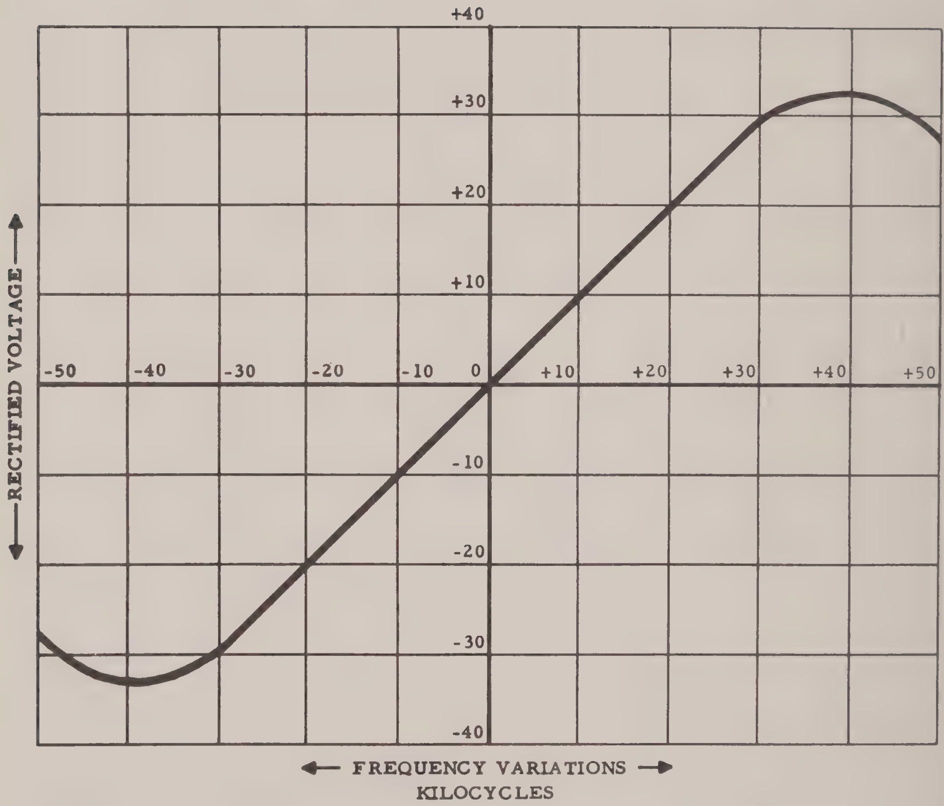
DISCRIMINATOR
FIGURE 10



MOTOROLA CAPACITANCE DISCRIMINATOR
FIGURE 11A



BRIDGE CIRCUIT
FIGURE 11B



DISCRIMINATOR RESPONSE CURVE
FIGURE 12

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Name ______________________ Student No. ______

Street ________________ Zone ____ Date ______

City ______________ State ________ Grade ______

EXAMINATION LESSON RA-7

1. Two vectors have a phase displacement of 90 degrees. Something causes the vectors to become more "in phase". The resultant vector will (increase)(decrease)(remain the same).

2. In normal operation, the discriminator produces changes of voltage at its output from changes of ______________________ at its input.

3. A discriminator is properly tuned and an unmodulated RF signal producing the center frequency is applied. The discriminator output is now (zero)(positive)(negative)(an audio voltage). When the incoming signal is frequency modulated, the output becomes an (RF)(IF)(audio) voltage, the amplitude depending upon the (rate of deviation)(amount of deviation).

4. For a Motorola discriminator, the primary of the discriminator transformer is tuned by observing meter position ______________. The secondary is tuned according to the reading of meter position ______________.

5. In figure 10, the path of the rectified DC current of diode D2 is through these components: ______________________.

6. A discriminator is properly tuned and the center frequency is being applied. As the signal is increased in amplitude, the reading on meter position 4 will:

   A. Increase ______________.
   B. Remain the same ______________.
   C. Decrease ______________.
   D. Change according to the signal strength. ______.

7. The discriminator in figure 10 produces an output of 6 volts when the applied signal has a deviation of 10 kc. When the deviation is increased to 15 kc, we might expect an output voltage of ________ volts.

8. In the circuit of figure 10, capacitor C3 opens. Besides a possible increase in output voltage for all frequencies, it is probable that the higher audio frequencies will: (check all correct answers).

   A. Become louder than the lower frequencies ______________.
   B. Have a lower amplitude compared to the low audio frequencies ______________.
   C. Will remain the same compared to the lower audio frequencies ______________.

9. A discriminator has a response curve which is linear 15 kc above and below the intended center frequency. An incoming signal is 5 kc off channel and the deviation is plus or minus 15 kc. The audio output (will be distorted)(will not be affected).

10. The principal purpose for using emphasis in the receiver is to: (choose only one answer).

   A. Reduce the amplitude of the high audio frequencies. ______________.
   B. Reduce the high-frequency noise. ______________.
   C. Restore the audio to its normal balance between the highs and lows. ______________.
   D. Improve the low frequency response. ______________.

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RADIO COMMUNICATIONS

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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-8
FM RECEIVERS

Squelch and Audio Circuits

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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-8
FM RECEIVERS

Squelch and Audio Circuits

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
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PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

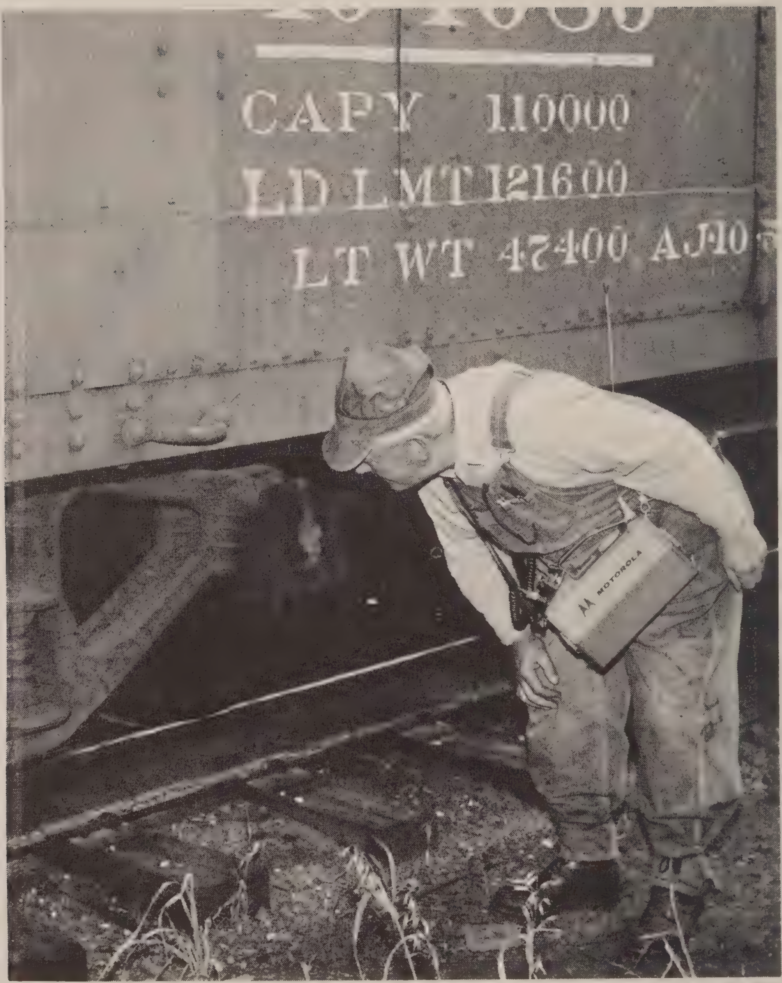
SQUELCH AND AUDIO CIRCUITS

LESSON RA-8

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.



Car checking and inspection — with immediate reports back to the engineer, the conductor or the yardmaster via "Handie-Talkie" two-way radio is one of the many uses of electronics in the railroad industry. Getting trains "on-the-road" faster, more safely boosts customer service and profit.

SQUELCH AND AUDIO CIRCUITS

Lesson RA-8

Introduction

As we listen to the sound portion of a television program or to an FM broadcast receiver, we do not hear any noise or hiss from the speaker when the audio modulation is temporarily removed. The reason for this is that the carrier is still present to keep the receiver quiet even after the audio modulation (representing the transmitted message) is discontinued. When the station finally signs off for the night, however, the carrier is removed. Unless the receiver has a squelch circuit, noise is now heard in the speaker.

This is not the case in two-way communications practice. As soon as the transmission is completed, the carrier (as well as the modulation) is discontinued at the transmitter. Without some means of silencing the receiver during these periods, the constant noise soon becomes bothersome. This receiver silencing is accomplished automatically by means of the squelch circuit, which prevents the noise voltages from reaching the speaker whenever the carrier is removed.

The incoming signal---whether modulated or unmodulated---controls the squelch operation. When the carrier is received the squelch "opens," and the receiver operates normally; in the absence of the carrier the squelch "closes," preventing noise voltages from passing through the audio stages. The squelching (which actually silences the receiver) must not be confused with a similar expression, "receiver quieting", which is the noise reduction at the limiters in the presence of a signal.

Squelch Requirements

Here are the requirements of the squelch circuit:

1. The squelch must quiet the receiver during periods of no signal.

2. The squelch must not interfere with receiver operation for weak signals.

3. The squelch should not operate on strong noise pulses or other interference coming into the receiver.

4. Fading signals must not cause fluttering--opening and closing of the squelch with the changing signal.

5. Squelch action must be independent of supply voltage changes. It should not be necessary to readjust the squelch control for normal changes of supply voltage.

6. The squelch must "open" completely for weak signals coming into the receiver.

The controlling voltage for figure 1--the voltage that initiates the action--is the negative grid bias of the limiter. With no signal present, this bias is low and the limiter plate current is high. With a signal present, however, the grid becomes highly negative (depending upon the strength of the signal) and the average plate current is reduced. It is this action which controls the bias on the audio stage and determines whether the receiver squelch is "open" or "closed."

NO SQUELCH

SQUELCH

The Squelch Circuit "Silences" the Noise Present in the Communications Receiver When No Signal is Being Received.

A Simple Squelch Circuit

Although the simple squelch arrangement of figure 1 would hardly be satisfactory in the modern communications receiver, it serves as a convenient starting point for our study. Like most squelch circuits, it renders the first audio amplifier inoperative when there is no signal coming into the receiver.

In the absence of a signal, the audio amplifier is biased beyond plate current cutoff so that noise voltages coming from the discriminator cannot get through to the speaker. When a signal is received, however, the bias on the audio stage is restored to normal, the signal from the discriminator is amplified in the usual manner and the message is reproduced by the speaker.

With no signal being received, the bias voltage at the first audio stage is adjusted until the tube is at plate current cutoff (easily recognized by the reduction of noise in the speaker). To accomplish this, the variable cathode resistor (R4) of the audio amplifier is adjusted so as to increase the positive voltage at the cathode, thus biasing the tube to cutoff. Resistors R4 and R5 constitute a voltage divider between B plus and ground, providing the necessary variation in cathode voltage.

The grid is returned to ground through R3, which is part of another voltage divider (R1, R2 and R3) connected between B plus and ground. The grid is therefore positive with respect to ground, as determined by the voltage across R3. Since both grid and cathode are positive to ground, the effective bias for the tube is the difference between these two positive potentials.

For example, if the grid is 50 volts positive but the cathode is 75 volts positive, the grid will be 25 volts less positive (or 25 volts negative) with respect to the cathode. This comparatively high bias prevents plate current in the audio stage. Any noise voltages applied to the grid cannot get through to the speaker.

The operation of the circuit depends upon a change of voltage taking place across resistor R3 in the grid circuit of the audio amplifier---this voltage must increase when a signal is applied. With a higher voltage across R3, the grid bias is reduced and the audio amplifier tube conducts.

You will recall that R3 is part of a voltage divider (R1, R2 and R3) which is connected between B plus and ground. So long as the supply voltage remains constant, the sum of the three voltages remains unchanged. Thus, if one of these voltages increases the other two must decrease.

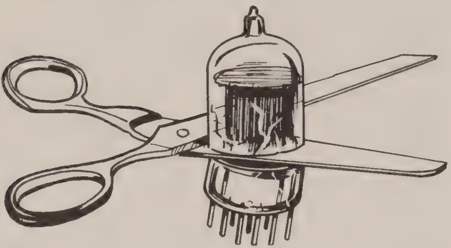
Resistor R1 of the voltage divider is also the plate load resistor for the limiter stage and carries the plate current of that stage. Any change of limiter plate current causes a change of voltage across R1. With no signal coming into the limiter, the limiter grid-leak bias is minimum and the plate current maximum. Maximum plate current through R1 produces a relatively high voltage across R1, and the voltages of R2 and R3 are correspondingly low.

When a signal is received, the negative grid bias at the limiter increases and the limiter plate current decreases. With less current through R1, the voltage across R1 must decrease; hence, the voltages of R2 and R3 must increase.

Let's assume that the voltage across R3 increases from 50 to 70 volts. The bias for the audio tube is now but 5 volts and the stage operates in the normal manner. (The cathode voltage remains relatively constant at a positive 75 volts with respect to ground.) The audio coming from the discriminator is now amplified and passes on to the speaker.

As soon as the message is terminated the incoming carrier is removed. The limiter bias is again minimum and the receiver is squelched. We say that the squelch is now "closed." The signal coming into the receiver causes the squelch to "open."

The important factor in the circuit operation is that the squelch control tube (the limiter in figure 1) becomes conductive without a



The Squelch Circuit Silences the Receiver Between Signals by "Cutting Off" the First Audio Tube.

signal and biases the audio stage to cut-off.[1]

Limitations of the Basic Circuit

There are certain limitations in the basic squelch circuit just described. For one thing, supply voltage variations cause a change in the fixed bias voltage at the audio cathode, making it necessary to readjust the squelch control setting. If the cathode voltage increases due to the increase of supply voltage, the bias becomes too high and the squelch may not open for weak signals.

When noise pulses of high intensity enter the receiver they produce a negative bias at the limiter and open the squelch. The open squelch allows these sharp noise pulses to be heard in the speaker. If the squelch is set high enough to avoid this "triggering" action, however, the circuit will not respond to weak signals.

The amount of bias change on the audio stage is determined by the change of limiter plate current, and this in turn depends upon the strength of the signal received and the resulting grid-leak bias at the limiter grid. Thus, a weak signal causes only a slight increase in limiter bias and correspondingly little bias-reducing action at the audio grid. The audio stage now operates at the lower portion of its operating curve, which means that the amplification will be very low and the output will be weak. Weak signals picked up by the antenna need all the amplification possible ---the audio stage should provide maximum gain.

Another objectionable feature of the basic squelch circuit of figure 1 concerns fading. Fading signals produce a changing limiter bias and a variable audio bias. This varies the amplification of the audio stage so that the output fluctuates with the signal level.

Besides these limitations, there is another reason why this simple squelch circuit could not be used in the modern communications receiver. The circuit of figure 1 depends for its operation upon the change of limiter grid bias. In the highly sensitive communications receiver the last limiter is always at saturation, whether a signal is being received or not. Because the limiter grid-voltage is essentially constant, there is no changing voltage to operate the squelch. Thus, it is necessary to find another means of controlling squelch operation and this leads us to the Motorola noise-compensated squelch circuit.

1. See TM 11-668 FM Transmitters and Receivers, page 171.

Motorola Noise-Compensated Squelch

The complete squelch circuit as used in the Motorola communications receiver is shown in figures 2 and 3. For convenience of analysis we have divided the circuit into the "control" section (figure 2) and the "noise" section (figure 3).

In figure 2 the DC amplifier becomes the squelch control stage for the first audio amplifier, and performs the same function in controlling the audio bias as the limiter stage of figure 1. This DC amplifier either conducts, biasing the audio amplifier to cutoff, or becomes nonconductive so that the audio can operate normally. Thus squelch operation is realized through the bias of the DC amplifier.

Resistors R1, R2 and R3 in the plate circuit of the DC control tube serve the same purpose as the corresponding resistors in figure 1. The variable squelch bias for the audio amplifier is again the voltage developed across R3. When the DC control tube conducts, the voltage at the audio grid becomes less positive (negative to the cathode) and the audio stage cannot operate.

When the DC control tube stops conducting, the voltage of R3 increases and unbiases the audio grid. The cathode circuit of the audio amplifier is similar to that of figure 1 in that a voltage divider is used to establish a DC voltage at the cathode. This cathode voltage, however, is fixed rather than variable. The "squelch control" adjustment is incorporated in the noise section rather than in the cathode of the audio stage.

In order to control the squelch operation, the bias on the DC control tube must be either highly negative (in order that the tube does not conduct) or it must be near zero, so that the tube conducts and cuts off the audio.

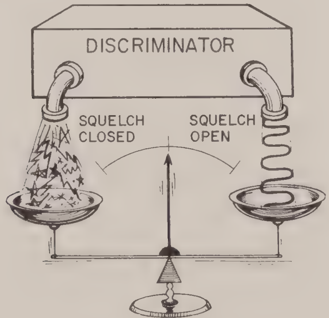
The bias of the DC amplifier depends upon two separate DC voltages: (1) a negative voltage available from the grid of the limiter stage--this voltage is present at all times--and (2) a positive voltage from the noise section of the squelch circuit. This positive voltage is variable.

Without an incoming signal the noise is high and a strong positive voltage (from the noise section) is applied to the grid of the DC amplifier. With a signal, however, the noise input to the noise section is greatly reduced and the positive voltage to the DC amplifier grid is similarly lowered. As we shall soon see, this variable voltage from the noise section determines whether the squelch will be open or closed.

In figure 2 we have used a battery to represent the positive voltage from the noise section; and, to show that this voltage may not always be present, we have included a switch between the battery

and the grid of the DC amplifier. We are now ready to analyze the squelch operation, as controlled by the two DC voltages at the control tube grid.

When a signal is received, little or no noise is applied to the "noise" circuit (figure 3) from the discriminator, and the output of the noise section may be considered as zero. This means that the switch in figure 2 is open. The only voltage at the grid is the strong negative voltage from the grid of the limiter. This bias (approximately 20 volts) is sufficient to prevent the DC tube from conducting. As a result, the audio stage is biased normally and the signal reaches the speaker.



The Discriminator Output May Be Either Noise, Audio, or a Combination of Both, Depending Upon the Strength of the Incoming Signal. Noise Closes the Squelch; a Signal Opens the Squelch.

As long as the carrier is coming into the receiver, the noise applied to the noise section is very low (due to the action of the limiters) and the receiver squelch remains open. As soon as the carrier is removed, however, the squelch closes.

With no carrier to provide noise reduction in the limiters, the discriminator output is essentially a strong noise voltage which, in turn, reaches the noise section of the squelch. As a result, a high positive voltage appears at the output, and this positive voltage is applied to the DC amplifier grid circuit. (This is the same as if someone closed the switch in figure 2.) This positive voltage counter-acts the negative voltage from the limiter grid, with the result that the voltage at the DC amplifier grid is approximately zero. Without bias at the grid, plate current is established in the DC amplifier and the receiver is squelched. Noise coming from the discriminator cannot get through the audio amplifier.

From this discussion we see that the noise section (figure 3) must in some way supply a positive DC voltage to the grid of the control tube when there is no signal. Furthermore, this positive voltage must be removed when a signal comes in. Keeping this in mind, let us now see how the noise section of the squelch circuit operates.

In the combined circuit of figures 2 and 3, the battery voltage of figure 2 represents the DC voltage across capacitor C1. This voltage is present whenever there is no signal coming in, but it is removed whenever a signal is applied.

In figure 3, the discriminator output is applied to the grid of the noise amplifier. With no signal entering the receiver, the discriminator output consists of noise voltage only, having a wide range of frequencies. When a message is received, the discriminator output contains very little noise and consists mainly of voice frequencies in the 300-3000 cps range. The coupling capacitors in the noise amplifier stage are chosen so that the lower (audio) frequencies are attenuated while the higher (noise) frequencies are allowed to pass.

Thus, when noise is present (with no signal applied) the input to the noise rectifier is high and its DC output voltage is also high. With a signal, the noise output of the discriminator decreases, and the noise input to the rectifier drops to a low value. The rectifier output is now approximately zero.

The noise rectifier operates the same as the power-line rectifier in a small table model radio. The rectifier is connected so that the output voltage is positive, and two filter capacitors (C1 and C2) maintain the output voltage at a steady DC level. This DC voltage to the grid of the control tube tends to make the grid positive to ground. Actually, this positive voltage opposes the negative voltage of the limiter grid and the net voltage at the DC amplifier grid is near zero.

The variable resistor in the cathode of the noise amplifier becomes the squelch control. The cathode bias on the noise amplifier determines the gain of the stage and thus regulates the amount of noise voltage applied to the rectifier. In this manner the squelch control determines the amount of rectified DC output voltage applied to the grid of the DC amplifier, and thus controls the bias and conduction of that tube.

The Variable Squelch Control is Usually Located on the Control Head of the Mobile Two-Way Radio.

As soon as a carrier is received, the noise output from the discriminator decreases, due to limiter action, and the input to the noise amplifier consists mainly of voice frequencies. Because of the low-frequency discrimination of the coupling capacitors, the input to the rectifier is small and the positive rectified output voltage decreases. In the absence of any high positive voltage from the noise amplifier, the grid of the control tube becomes very negative and the tube cannot conduct. The squelch is now open. Because of this action at the grid of the control tube, the squelch will open on very weak signals.

The positive opening of the squelch for weak signals is further insured by using a common cathode resistor for the DC control tube

and the audio amplifier. When the audio tube conducts, the current through this resistor increases, increasing the bias across the common bias resistor. (The audio stage is so designed that its plate current is considerably greater than that of the DC tube.) With this increased bias voltage applied to the control tube, cutoff is definitely assured.

The Motorola noise-compensated squelch circuit receives its name because of its freedom, both from supply voltage variations and from noise levels coming into the receiver. Let's see how this is accomplished.

Supply voltage changes cause corresponding changes in the gain or amplification of the various stages of the receiver. If the voltage should increase, the noise reaching the limiter stage also increases to produce a greater negative grid voltage. This negative voltage tends to make the grid of the DC control tube more negative. At the same time, however, the noise at the noise amplifier and rectifier also increases and produces a higher positive output from the rectifier.

These two DC voltages, the negative from the limiter and the positive from the noise rectifier, counteract each other and the grid voltage at the DC amplifier remains constant. Thus, the squelch operation is immune to supply voltage variations.

Increases in noise voltages entering the receiver balance out at the DC amplifier grid in much the same manner. The higher noise level at the limiter grid may increase the grid bias, but the DC output from the noise rectifier also increases and the voltage at the DC control tube grid remains constant.[2]

There is an action, however, known as "clamping" that may take place in squelch circuits not specifically designed to avoid this effect. If steps are not taken to counteract clamping, the receiver may not reproduce weak signals.

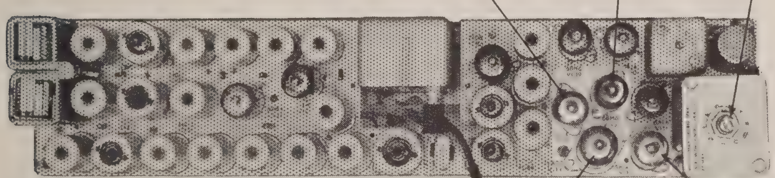
Clamping

Basically, clamping is a condition whereby the squelch of the receiver opens normally with the application of a carrier, but as soon as the operator at the transmitter talks into the microphone, the squelch circuit in the receiver closes and the message is not heard. The squelch circuit may remain in the clamp condition for as long as the incoming carrier is modulated. Clamping may be the result of any of three different factors taking place within the receiver. We shall discuss each of these conditions separately.

1. An incoming unmodulated carrier may be at the threshold level of the receiver so that the squelch is open, but, due to the limited quieting produced at the limiters, some noise remains. As soon as the carrier is modulated, the carrier level is automatically reduced. (In modulating the transmitter, energy is taken from the carrier and placed in sidebands.)

2. See TM 11-668 FM Transmitters and Receivers, pages 172-175; also "Motorola Patented Squelch Circuit", reference R8.

As a result of the lower signal level at the limiters, there is less noise quieting and the noise increases at the noise amplifier and rectifier. The positive output from the noise rectifier increases and the receiver goes into clamp---the squelch closes. As we shall soon see, Motorola has devised an "anti-clamp" circuit which prevents this condition.



This Photo Shows the Location of the Audio and Squelch Circuit Components.

2. The second possibility of clamping in the receiver results from the modulation of the transmitter by high-frequency voice signals (such as "sss") which have a strong high-frequency component. This looks like noise to the receiver circuits and produces an increased output from the noise rectifier. As a result, the receiver clamps.

The remedy is to control the modulating signal at the transmitter. The Motorola Instantaneous Deviation Control circuit (which we shall study in the transmitter portion of this training) limits the modulation of the transmitter by these undesirable high-frequency components and thereby eliminates this type of clamping at the receiver.

3. The third possibility of clamping comes about when the incoming signal is overdeviated---again a factor to be controlled at the transmitter. At the receiver, the sideband energy of the overdeviated signal falls outside the acceptance of the Permakay filter and less energy reaches the limiters. With less energy applied, the limiters allow more noise into the noise section of the squelch circuit and the receiver clamps.

Anti-Clamp Circuit

The anti-clamp circuit of figure 3 has been developed, patented and used by Motorola in their communications receivers.

The anti-clamp action can be broken down into three distinct operations: (1) voice frequencies are introduced into the noise amplifier, (2) the noise amplifier operates as a limiter when voice signals are present along with the noise, and(3) only the noise pulses from the amplifier-limiter are allowed to reach the noise rectifier.

The coupling circuit between the discriminator and the noise amplifier allows the upper voice signals (as well as the noise) to reach the grid of the noise amplifier. Only the RF filter and the RC coupling circuit are in this path, and the output voltage of the discriminator is thus applied to the amplifier.

Noise alone, applied from the discriminator to the noise amplifier, provides some clipping of the noise voltage peaks in the plate circuit of the amplifier. This results in near maximum output voltage from the stage into the noise rectifier. When a modulated signal is received, voice signals reaching the amplifier drive the stage into full limiting. As a result, the noise energy in the plate circuit of the amplifier, and thus the total noise applied to the noise rectifier, are lowered.

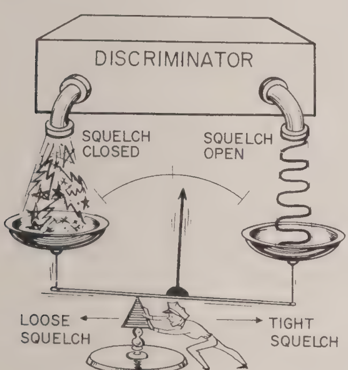
Two factors are responsible for this limiting action. First, the voice signals have a high amplitude and swing the plate current to saturation and cutoff. That is, on the positive peaks the voice signals drive the stage to saturation, and on the negative peaks the grid is far beyond cutoff. Second, the voice frequencies are lower than those of the noise---one cycle of voice energy lasts longer than one cycle of noise. The amplifier is thus held at cutoff and saturation for a large percentage of the time. The time periods when noise can get through the stage are relatively short.

The operation of the noise-amplifier-limiter stage with voice signals present is the same as that of the limiter stages preceding the discriminator when an IF signal is applied. Just as the IF signal replaces the noise in the limiter output to provide receiver quieting, voice signals entering the noise amplifier stage reduce the amount of noise in the plate circuit. At the limiter section the noise is undesirable, and two limiters are used to reduce the noise to a minimum. In the noise section, our goal is merely to control the amount of noise reaching the rectifier---the amount of noise must not increase during modulation.

Only the noise component remaining in the plate of the limiter-amplifier reaches the rectifier---not the voice signals. This is due to the attenuation of the voice frequencies in the coupling circuit between the noise amplifier and the noise rectifier. With less noise voltage applied to the rectifier, the positive output voltage decreases. Now let's see how this action prevents clamping.

The modulated FM signal, we have said, allows a higher noise level at the discriminator, and,

without anti-clamp provisions, this additional noise reaching the noise amplifier and rectifier causes the squelch to close (clamp). A higher noise level reaches the noise amplifier when the carrier is modulated, but in the Motorola circuit of figure 3 there is also a strong audio voice signal that drives the amplifier to full limiting. The noise energy reaching the noise rectifier cannot increase---in fact, it will generally decrease. With the positive voltage from the rectifier remaining constant or decreasing, the squelch circuit does not close ---there is no clamping.



The Setting of the Squelch Control Determines the Relative Ability of the Noise and Signal Coming From The Discriminator to Open and Close the Squelch.

The operation of the anti-clamp circuit depends, then, upon the presence of audio (voice voltages) at the noise amplifier at the time the carrier is modulated. It is this voice signal which limits the noise output from the amplifier to the noise rectifier. [3]

3. See reference R-8.

Note that while the coupling capacitors associated with the noise amplifier play an important role in passing certain frequencies, this is accomplished only in conjunction with its associated resistors. This should be kept in mind by the serviceman making any parts substitutions. The values of these resistors (as well as the coupling capacitors) are critical and must not be altered if it becomes necessary to replace them.

Squelch Threshold and Squelch Setting

If the squelch does not open for weak signals the receiver is effectively dead, even though the desired "message" is available at the first audio stage from the discriminator. For example, if the squelch does not open for signals weaker than one microvolt, these weak signals do not get through to the speaker. Thus it can be seen that the opening of the squelch circuit determines to a considerable degree the sensitivity of the receiver.

A well-designed squelch circuit will open for signals below the 20-db quieting sensitivity rating of the signal circuits, and thus the squelch does not interfere with the operation of the receiver. Because the weakest signal producing any degree of intelligence is that which causes about 3 or 4 db of quieting, the squelch must be completely open for this signal level coming into the receiver.

The opening of the squelch on weak signals is affected by the setting of the squelch control. This control must be adjusted so that, without a signal coming in, the noise is just quieted or squelched. If the control is advanced still further the positive bias at the control tube increases and it takes a stronger signal to open the circuit. This in turn affects the squelch sensitivity and the weak signal may not be heard.

Summary of Squelch Operation

Squelch is realized through the control of the first audio amplifier DC grid bias. With the squelch closed, noise coming into the antenna or generated within the receiver cannot reach the speaker. As soon as a signal comes in, the squelch opens and allows normal reception.

When the control tube is conductive, the audio stage is disabled. In order to open the squelch, the positive voltage due to noise is lowered and only the negative limiter bias voltage is applied to the grid of the control tube. This negative voltage prevents that tube from conducting, which in turn allows the audio tube to operate.

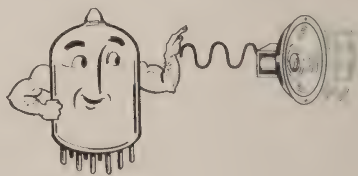
The Motorola noise-compensated squelch offers the advantages of (1) making the circuit immune to noise pulses, (2) making the operation more positive for small input voltages, (3) providing for a quick opening response, and (4) making the squelch circuit independent of supply variations. Also, by applying higher-frequency voice signals from the discriminator to the noise amplifier, the squelch circuit cannot clamp on weak signal inputs.

The Audio Amplifiers

The audio signal reaching the first audio amplifier is usually less than one volt, and an audio section is therefore required in order to operate the speaker.

A typical Motorola circuit is shown in figure 4. Capacitor C1 and resistor R1 form the deemphasis network, and the corrected audio voltage is available across C1. The volume control parallel to C1 determines the amount of audio voltage applied to the grid of the first audio amplifier. The bypass capacitor between the plate load and the decoupling resistor prevents noise on the B supply line from entering the audio system at this point.

The second audio stage---the power amplifier---provides the power needed to properly operate the speaker. The bypass capacitor from plate to ground reduces the amplitude of the higher audio



The Audio Output Stage in the Communications Receiver Furnishes the "Power" to Operate the Speaker.

frequencies (above 3000 cps). The circuit is quite straightforward except for its bias arrangement.

A fixed bias for the power amplifier is obtained from the grid circuit of the second limiter. With no signal present, the noise alone provides an appreciable amount of grid-leak bias---little increase is seen in the bias of this stage even when a signal is received. (The plate of the first limiter is already at saturation for the noise present.) Thus the second limiter bias remains relatively constant at all times and provides a convenient source of fixed bias for the audio output stage.

A voltage divider parallel to the grid circuit of the limiter establishes the desired amount of bias for the audio grid. This arrangement permits a higher plate-cathode voltage than would be possible if the more common cathode bias were used, and the tube is thus capable of furnishing more audio power to operate the speaker. Also, by eliminating the higher wattage cathode resistor and high-capacitance bypass capacitor usually associated with cathode bias, the circuit of figure 4 is more economical.

A step-down type of output transformer is used to match the impedance of the plate circuit to the impedance of the speaker voice-coil, usually about 3 or 4 ohms. The speaker is specifically designed to give greatest clarity to the voice signals, thereby improving the "readability" of the message. Output power of this receiver is limited to approximately two watts and, in most applications, is sufficient to reproduce the average message with good volume. [4]

Volume Control Circuits

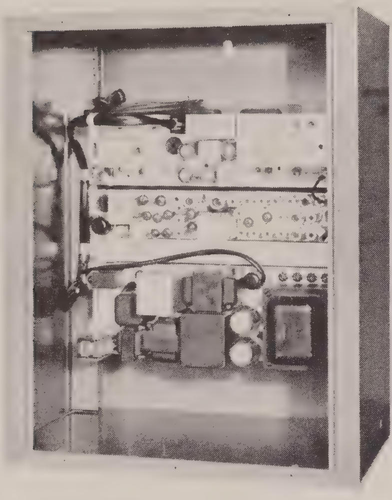
There are several features of two-way communications equipment which make it inconvenient to use the conventional type of volume control found in tv and other receivers. The major problem concerns the long distance between the operator's control head and the receiver chassis.

Because any noise picked up in this long line will be amplified in the audio stages along with the low-level audio signal, the conventional type of control must have a shielded cable, both from the receiver to the control head and from the control head back to the receiver.

There are two possible solutions to this problem of volume control: (1) the pad type control and (2) the DC control. Each has its advantages and disadvantage. We shall discuss the pad type first.

The pad control (figure 5) makes use of a low-impedance pot and suitable circuit at the control head, connected in the audio supply line to the speaker. Because this audio line is of low impedance and has a high power level, and because there is no further amplification, the shielded cable is not required. Any noise pickup is small (compared to the signal) and will not be heard.

4. See TM 11-662 Theory and Applications of Electron Tubes, pages 127-142; also TM 11-668 FM Transmitters and Receivers, page 175; also FM Transmission and Reception, by Rider and Uslan, pages 327-330.



Here We See a Mobile Type Transmitter and Receiver Used as a Base Station and Operated from an AC Power Supply.

The pad control introduces some insertion loss, due to the pot being parallel to the speaker supply line. The attenuation is small, however, and does not appreciably reduce the power to the speaker. There is also a certain amount of mismatch, but again this is relatively small and does not cause noticeable distortion. Thus, the pad type control has the characteristics of nearly full output power with little distortion.

The second type of control--the DC volume control--is shown in figure 6. The DC volume control adjustment affects the voltages of three stages within the receiver. These are (1) the bias of the first audio amplifier, (2) the plate and screen voltages of the second limiter, and (3) the cathode bias of the noise amplifier.

The DC volume control circuit avoids the use of shielded cables by making use of DC voltages to regulate the volume. Two additional advantages are found in this type of circuit. First, because there is not attenuation of the audio signal due to the volume control, maximum audio output is realized. Second, there is a minimum amount of distortion with the control set at an average listening level.

The actual volume control is realized by varying the bias of the first audio amplifier stage. As the volume is reduced to a lower setting, the bias on the stage is increased and the signal operates on a lower portion of the characteristic curve. Since the gain of the stage depends upon its bias, this means less amplification and a lower audio output.

As the DC volume control is adjusted to a low level, the audio stage operates on the lower portion of the characteristic curve and, due to the non-linearity of the curve at the lower portion, strong audio inputs may be distorted. To minimize this distortion, the circuit is arranged so that the limiter output voltage is also reduced when the volume control is adjusted to a lower level.

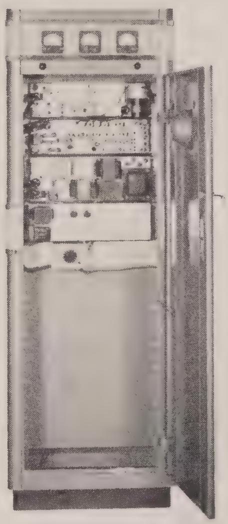
As shown in figure 5, this is accomplished by lowering the plate and screen voltages. This in turn lowers the plate saturation level

and produces a lower limiter output voltage, resulting in a smaller audio voltage from the discriminator. This lower audio signal applied to the audio amplifier does not operate over as wide a portion of the characteristic curve, and the distortion is reduced.

The change of limiter output voltage is usually about a 5-db ratio from maximum to minimum settings of the volume control, which represents a voltage ratio of almost 2 to 1 for the limiter voltage. (6 db is a 2 to 1 voltage ratio.) Thus, the change in limiter operation provides a smaller output voltage which in itself results in a smaller signal to the audio stage; at the same time, the lower audio voltage produces less distortion in the audio stage, by operating over a smaller portion of the characteristic curve.

The third circuit involved in the DC volume control is the noise amplifier stage. The object here is to compensate for the noise level available from the noise amplifier when the receiver is in squelch. When the volume control is set for a low level of audio output, the noise available from the limiter (during times of no signal) is reduced and there is less noise at the rectifier. If this condition went uncorrected, setting the DC volume control would also require resetting the squelch control.

By reducing the bias on the noise amplifier when the volume control is at a low setting, the gain of the noise amplifier stage is increased so that the same amount of noise reaches the noise rectifier regardless of the volume control setting. Also, when receiving very weak signals, some noise reaches the noise section of the squelch. Variation of the noise amplifier bias by means of the volume control maintains a constant noise level



A 450-MC Base Station. The Transmitter is at the Top, Followed by the Receiver, Power Supply and Control Panels.

(by counteracting the change in noise output from the limiter) so that the squelch sensitivity does not change for the reception of weak signals.

While the DC volume control has several advantages, the nature of its circuitry does not readily lend itself to certain specialized

applications. These involve the use of tone controlling signals to operate the receiver (Quik Call and Private Line receivers).

These receivers require a constant level of the audio controlling tones (which are used to trigger the receiver). If the level of the audio reaching the controlling circuits should change with the setting of the volume control, the sensitivity of the receiver will change correspondingly. Thus, it is necessary to use a volume control circuit which maintains a constant audio level in the audio amplifiers. Since this is achieved by the pad type control, this circuit is used exclusively in such receivers. (It is not our purpose at this time to discuss Quik Call and Private Line receivers. Later lessons will deal exclusively with these circuits.)

In addition to either the DC or the pad control, it is desirable to include a level setting control as shown in figure 4. This is the same as a conventional volume control, but it is not used by the operator to adjust the volume to the desired level. Instead, the adjustment is made by the serviceman. This control is located on the receiver chassis and the unit must be removed from the housing in order to make an adjustment.

The level setting control compensates for variations in the audio gain and, in conjunction with the volume control on the control head, allows for optimum operation. The level control must be adjusted for an adequate output according to the requirement of the particular installation, but it must not be set higher than necessary. To do so will only overdrive the audio amplifiers and produce unnecessary distortion.

In practice, the volume control on the control head is turned to maximum, after which the level setting control on the receiver chassis is advanced to the maximum required output at the speaker. The operator may then select any desired volume ranging from zero (or a very minimum) to the preset maximum.

IMPORTANT WORDS USED IN THIS LESSON

CLAMPING: A form of undesirable squelch action which prevents the message from reaching the speaker. Although the squelch "opens" for the incoming unmodulated carrier, it "closes" again as soon as the carrier is modulated. This occurs (1) when the unmodulated carrier is weak and barely opens the squelch, or (2) when the transmitter is over-deviated to the extent that much of the sideband energy is beyond the bandpass of the receiver tuned circuits (Permakay filter). In either case, clamping is the result of the reduced signal amplitude reaching the limiters when the carrier is modulated.

CLOSED SQUELCH: The condition in which the squelch has operated to silence the receiver; noise voltages cannot get through to the speaker.

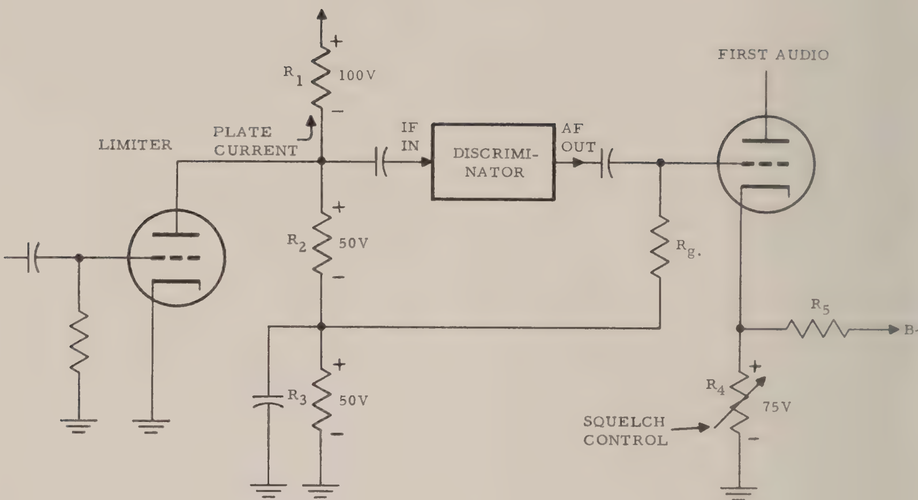
NOISE COMPENSATED SQUELCH: A circuit which utilizes the noise voltages (normally present in the receiver without a signal) to initiate and control the squelch operation.

OPEN SQUELCH: The condition in which the squelch is inoperative, with the result that the receiver may work normally. This condition is evidenced when a carrier is being received.

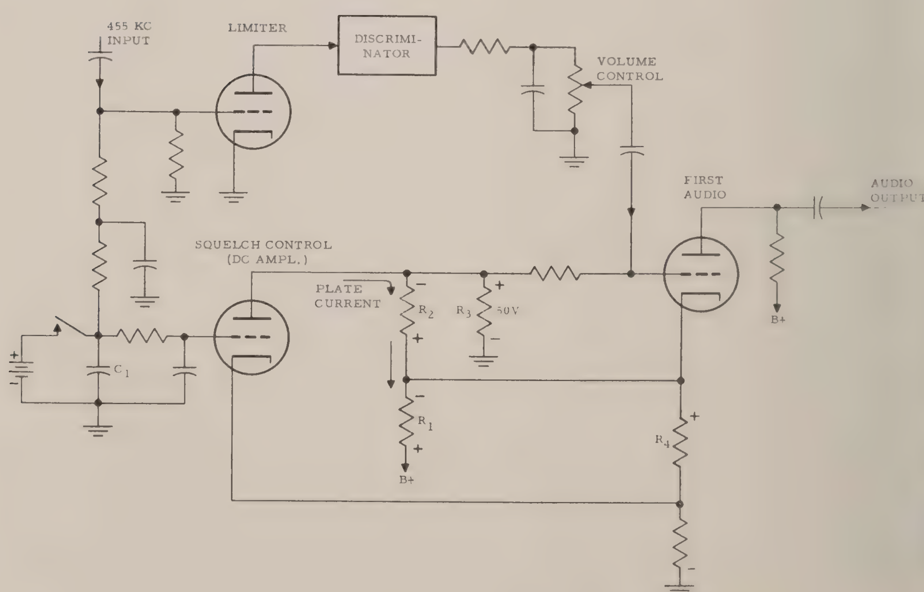
SQUELCH: A circuit which disables the audio section of the receiver in the absence of a carrier. As a result, the noise which is normally heard without a signal being received cannot reach the speaker.

SQUELCH THRESHOLD: The minimum setting of the squelch control which will permit the squelch to close; a weak signal at the receiver input will open the squelch.

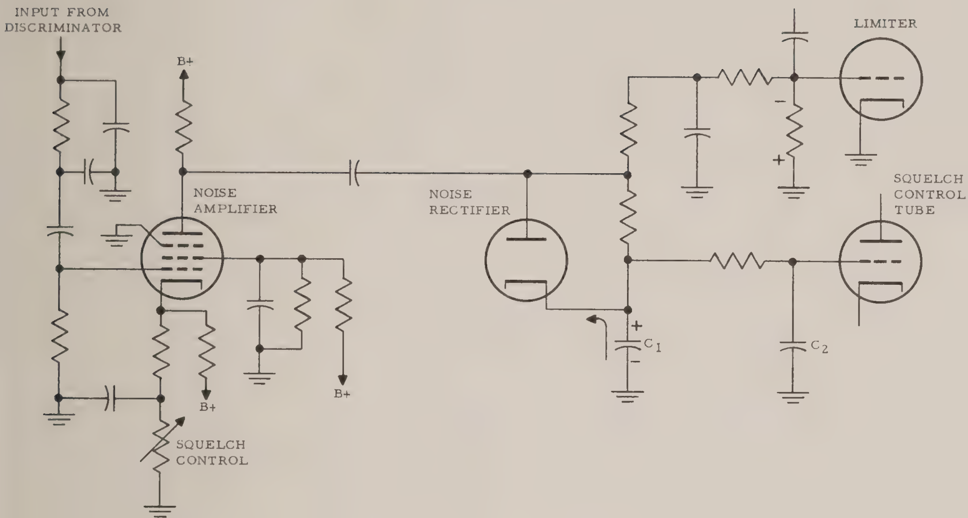
MAXIMUM SQUELCH; FULL-ON SQUELCH: The condition caused by adjusting the squelch control fully clockwise, producing an extremely high bias on the audio stage. A weak signal may not open the squelch--- there is a loss in receiver sensitivity.



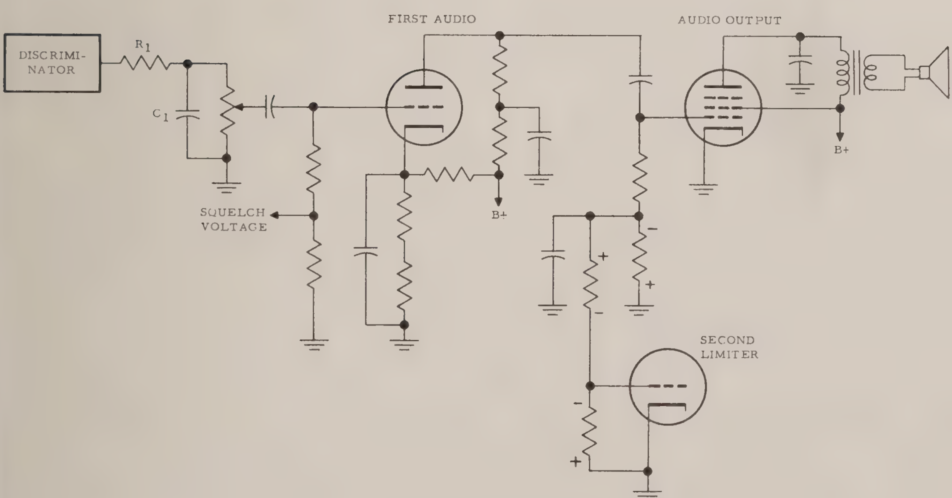
SIMPLE SQUELCH CIRCUIT
FIGURE 1.



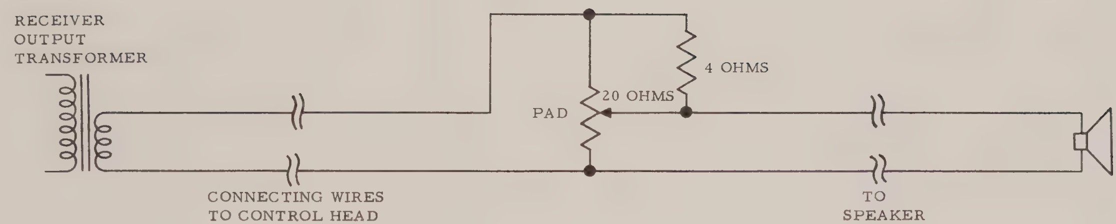
PARTIAL DIAGRAM -- SQUELCH CIRCUIT
FIGURE 2



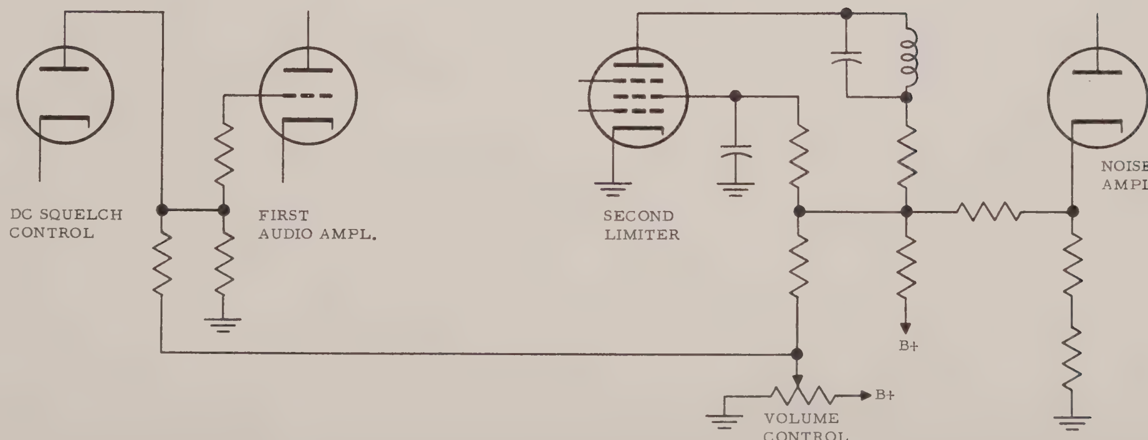
"NOISE" SECTION OF SQUELCH CIRCUIT
FIGURE 3



AUDIO AMPLIFIER SECTION
FIGURE 4



PAD TYPE CONTROL
FIGURE 5



"DC" VOLUME CONTROL CIRCUIT
FIGURE 6

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Name ______________________ Student No. ______

Street ______________ Zone ____ Date ______

City ____________ State _______ Grade ______

EXAMINATION LESSON RA-8

1. The squelch in the communications receiver serves to: (choose one answer).

   A. Silence the receiver when the incoming carrier is unmodulated. ____________.
   B. Reduce the amount of noise generated by the receiver. ____________.
   C. Biases the last audio stage beyond plate-current cutoff when the noise gets too high. ____________.
   D. Prevent noise voltages from reaching the speaker between messages. ____________.

2. The squelch circuit acts to (reduce)(increase) the negative bias of the first audio stage during periods of no signal.

3. Weak on-channel signals entering the receiver (should)(should not) cause the squelch to open fully.

4. In figure 2 of this lesson, the variable bias which controls the first audio stage is the voltage appearing across:

   A. The limiter grid resistor ____________.
   B. Resistor R3 ____________.
   C. Resistor R4 ____________.

5. In the Motorola noise-compensated squelch, two DC voltages are applied to the grid of the control tube. The negative voltage comes from ____________; the positive voltage comes from ____________ ____________.

6. Adjusting the squelch control of figure 3 of this lesson so that the gain of the noise amplifier is increased will (increase)(decrease) the input to the noise rectifier, which in turn causes a greater (positive)(negative) voltage output. This in turn makes the control tube (conductive)(non-conductive) and (opens)(closes) the squelch.

7. The coupling capacitors to both the noise amplifier and the noise rectifier are replaced with capacitors having much greater capacitance then the original units. The squelch is likely to remain open ____________ closed ____________.

8. In figure 2 of the lesson, resistor R2 increases to a very high resistance value. What will be the probable effect upon the receiver operation? (Choose <u>one</u> answer).

   A. Squelch always open. A. ________
   B. Distorted audio output; squelch operation normal. B. ________
   C. Squelch remains closed even when a signal is present. C. ________

9. The noise amplifier stage in a squelch circuit stops operating due to burned out filament. Will the squelch be always open or always closed? ____________.

10. The audio amplifier section of the communications receiver is designed to pass the (entire)(low)(high) range of audio frequencies. Voice frequencies are usually considered to lie between ____________ and ____________ cycles.

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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-9
FM RECEIVERS

The Meter in the Communications Receiver

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-9
FM RECEIVERS

The Meter in the Communications Receiver

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

THE METER IN THE COMMUNICATIONS RECEIVER

LESSON RA-9

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Two-Way Radio, by replacing hard-to-see hand signals, provides positive voice orders on a construction project — only one of the thousands of uses for "Handie-Talkie" pocket transmitters and receivers in business and industry.

THE METER IN THE COMMUNICATIONS RECEIVER

Lesson RA-9

Introduction

When the family television receiver suddenly stops working and is not repaired for a day or two there may be considerable family dissension, particularly from those younger, avid TV viewers. This is of no major importance, however, compared to the failure of a police or fire department's two-way communications system. Inoperation in such cases may jeopardize public safety.

You, as a service technician, will often be called upon to repair vital equipment, which obviously must be restored to operation immediately. The efficiency with which you go about this task will depend a great deal upon your ability to take and interpret meter readings in the receiver.

All well-designed equipment has some provision for quick monitoring of important receiver circuits by means of a meter, so that almost any trouble can be quickly isolated. Once a fault has been pinpointed to a small section within the receiver, the major part of the job is really finished.

Efficient Service of the Modern Two-Way Radio Requires Quick and Accurate Readings Within the Equipment.

The Important Circuits of the Motorola Two-Way Radio may be Measured by Plugging-In the Motorola Test Set and Turning a Selector Switch.

Consider, for example, the most probable trouble of all--a bad tube. Assuming the filament is not burned out, the offender cannot be located by a visual check. The bad tube might be found by starting at one end of the receiver and changing tubes until the faulty one is found, but such procedure is obviously inefficient and wastes valuable time.

By spending a minute or two in taking meter readings, the trouble may be isolated to a particular section of the receiver; then a few substitute tubes (at most) may be tried and the receiver is back in operation. A tube substitution, it is true, often necessitates a "touch up" of the alignment, but here too the intelligent use of meter readings simplifies what otherwise might be a lengthy or difficult job.

In this lesson we shall study the nature of various readings available in the modern communications receiver. We shall also determine what specific conclusions about the receiver operation can be deduced from these readings.

The Motorola Metering System

Figure 1 is a block diagram of a Motorola communications receiver. It is similar to the one included in lesson 2, but to this diagram we have added (1) the meter positions usually found in this equipment and (2) the location of the particular tuned circuits which must be adjusted to their correct frequencies. These tuned circuits are represented by arrows, each arrow indicating one tuned circuit.

Motorola has devised a rather unique metering system which allows a quick and accurate measurement of vital receiver circuits. (This applies to the transmitter as well as to the receiver). While other meters may be used to secure the same indications, the Motorola

test set (an auxiliary piece of equipment) allows almost immediate "viewing" of the circuits.

Each meter position has the necessary resistor and bypass capacitor connected internally in the receiver, and leads are brought out to separate terminals of a multi-terminal plug. The test set is plugged into the receiver; then, by merely turning a switch on the test set, the meter monitors the various circuits.

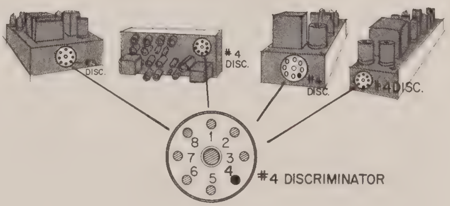
The meter position remains the same for almost all Motorola receivers. Switch position 4, for example, is always used to balance the discriminator secondary; regardless of the particular model being used, meter switch position 4 records the discriminator output. All meter positions applicable to the receiver of figure 1 are shown in figure 2 and we shall discuss each of these positions as we proceed with this lesson. [1]

Metering The High-Frequency Oscillator

With the test set plugged into the receiver and the switch at position 6, the meter indicates grid current in the high-frequency oscillator (figure 1). In the oscillator section we find three circuits that must be tuned or adjusted: (1) the oscillator grid tank (activity) circuit, which operates at the same frequency as the oscillator, (2) the "multiplier" circuits, which are tuned to some harmonic of the oscillator frequency, and (3) the "warping" adjustment, which controls the operating frequency of the oscillator.

Switch position 6 is used to adjust the oscillator grid tank only. This adjustment affects the amount of RF voltage generated by the oscillator; hence it determines the amount of harmonic output from the stage. At the same time, the activity adjustment does not change the oscillator frequency any appreciable amount. Measuring the amount of grid current at the oscillator and setting the activity adjustment to maximum thus provides optimum operation of the oscillator.

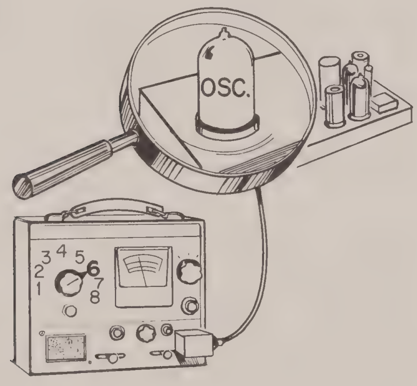
According to figure 2, the reading at position 6 for this particular receiver model may be any value between 12 and 40 on the meter and still be satisfactory and normal. This variation in readings



Each Switch Position of the Motorola Test Set has been Standardized. For Example, Switch Position 4 is the Discriminator Balance Test for all Receivers.

1. Later Servicing Lessons contain more details about the Motorola Test Sets and their use in service and alignment procedures.

from one receiver to another (which is due to the varying amount of crystal activity) demonstrates the importance of consulting the instruction manual. If he does not know that this particular reading may have a wide variation, the serviceman may conclude that a particular receiver measuring only 15 is not operating normally, because a reading of 35 or 40 was secured on similar model receivers.



In Switch Position 6 the Motorola Test Set Indicates the Oscillator Activity, by Measuring Grid Current.

The importance of consulting the instruction manual and of following the manufacturer's recommended procedures, is illustrated in making adjustments for oscillator activity. Certain types of oscillators cannot be adjusted for maximum or peak if they are to provide stable operation. Changes of tube operation or power supply voltages often cause these oscillators to suddenly stop operating, and the receiver is then dead.

For such oscillators, the tuned circuit adjustment must be to the "high" side (frequency-wise) of the maximum reading. Service manuals provide specific instructions regarding this adjustment, so that the final setting will allow continued operation in spite of the circuit variations. These oscillators are usually recognized by a sudden decrease in the current reading on one side of the maximum setting. On the other side the maximum, however, the decrease is gradual.

Where no specific instructions are given, it is always a good practice to set these oscillators slightly (about 95 percent) to the "gradual" side of maximum. It must be kept in mind that the activity circuit is the only adjustment within the oscillator stage that should be made when using meter position 6. Both the frequency and harmonic circuit adjustments are made when observing other meter readings.

The Meter in The Last IF Stage

The serviceman makes use of the grid current reading taken at the grid of the last IF amplifier. In communications receivers it is not uncommon to find the cathodes of the last IF amplifier stages grounded, and the only bias on these stages is that due to grid current. Except for some extremely small "leakage", grid current is evident only when a signal of some sort (noise or otherwise) is applied to the grid. Position 1 on the test set, in-

dicates the amount of signal or noise at the grid of the last IF stage.

By measuring the strength of the signal applied to the grid of the last IF stage, the meter in position 1 serves as an output meter for all the receiver stages between the antenna and the grid of the last IF. Thus, all of the tuned circuits which control the strength of the signal may be tuned to resonance by observing a maximum indication of the meter. The circuits which may be adjusted in this manner are the antenna and RF, the oscillator multiplier, the first IF, and the plate tanks of the first two stages of the last IF section.

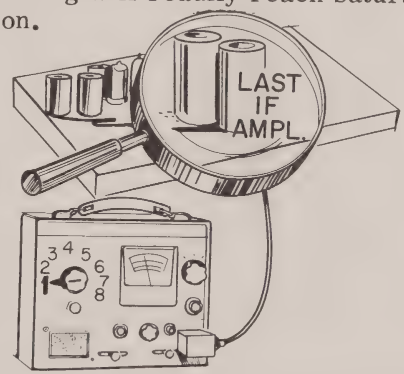
Figure 2 suggests a reading between -0.1 and -1.0 volt, and this is the average indication for the noise present without an incoming signal. An incoming signal produces a higher reading, the amount depending upon the signal amplitude. Strong signals may even produce saturation, although this is not the average condition.

Unless the receiver is aligned properly and receives a comparatively strong signal at the channel frequency, the reading of position 1 is very low---perhaps zero. For this reason it is usually necessary to use position 2, the grid of the following stage, for service and alignment procedures.

The reading of position 1, however, is useful where a strong signal is applied to the receiver and the reading of position 2 is in saturation. Because it is now impossible to use the reading of position 2, it is necessary to use position 1.

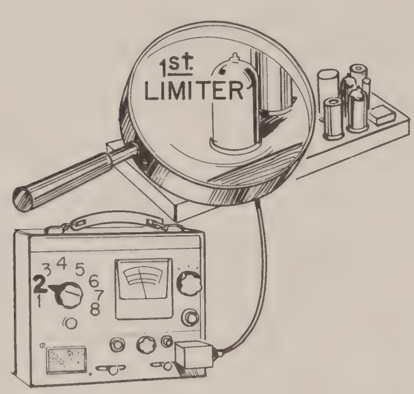
The Meter in The First Limiter

Figures 1 and 2 show meter position 2 as recording the grid current of the first limiter. The principles and factors discussed for position 1 apply also to position 2. Because of the additional amplification of the last IF amplifier stage, the noise or signal level at the first limiter grid will be higher then that of the preceding stage, and we can expect the readings, too, to be considerably higher. The tabulated range of -18 to -40 volts confirms this. With an average signal input, this reading will readily reach saturation.



In Switch Position 1 the Motorola Test Set Indicates the Signal (or Noise) Level at the Grid of the Last IF Amplifier.

In servicing receivers with low gain we find that the reading at position 1 is often too low to be of any use, but position 2 may provide a reasonable indication.



In Switch Position 2 the Motorola Test Set Indicates the Signal (or Noise) Level at the Grid of the First Limiter.

It is possible to use position 2 for adjusting all the tuned circuits listed for position 1 so long as the meter does not indicate saturation. Besides, since the tuned plate circuit of the last IF amplifier follows position 1 (insofar as the signal path through the receiver is concerned) it is necessary anyway to use position 2 in order to adjust that circuit. For the final adjustments of the tuned circuits,readings in position 2 usually show sharper changes and allow settings which are more exact.

Let's see how meter position 2 is used for receiver alignment. Assuming that an RF of the correct channel frequency is applied, and that the local oscillator is operating at its correct frequency, we may adjust the grid and plate of the RF amplifier, the multiplier circuits in the oscillator and the plate circuits of the mixer and 1st IF amplifier for maximum on meter position 2. (We can also adjust the plate circuits of the 2nd IF amplifier stages in the low-frequency IF section, but these circuits are tuned by an alternate method, discussed later in this lesson.)

When using the meter in position 2, the possibility of saturation must always be kept in mind. Once the stage has reached saturation, there will be no changes in the reading for further increases of applied signal. This is particularly important in using the meter for alignment. The signal into the receiver must be kept low so that the meter deflection is near the center of the dial.

The reading of position 2, with noise input only, is often used to determine the general sensitivity of the receiver. The amount of noise, as shown by the meter reading, indicates the amplification and allows a reasonable deduction concerning the receiver sensitivity.

Metering The Discriminator

The meter positions discussed up to this point provide for the adjustment of all circuits except those of the discriminator transformer and the oscillator frequency.

The discriminator transformer has a tuned primary and secondary and both these circuits are tuned

to the second or low IF frequency. Because of the importance of having both these tuned circuits resonant at the center frequency, Motorola has provided a separate meter position for each.

Switch position 5 is used to adjust the primary, and position 4 is for the secondary. The intelligibility of the reproduced message depends a great deal upon the proper adjustment of these circuits, for considerable distortion may result if the circuits are not resonant to the center frequency. This applies to both the primary and the secondary.

There is a very good reason for having separate meter positions for tuning the primary and secondary of the transformer. The meter in the discriminator secondary is necessary to properly adjust the secondary for zero output. If we attempt to tune the primary by observing the secondary reading, we run into trouble.

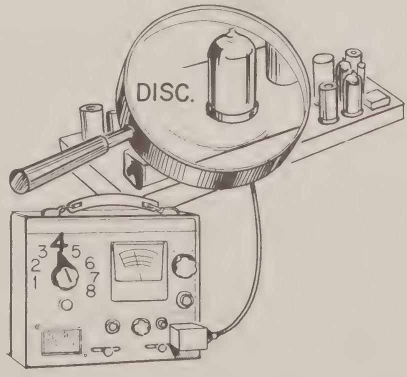
When the secondary is balanced or at zero there is no deflection when we adjust the primary. If the secondary is off resonance, the reading is due to a frequency either above or below center. To tune the primary for maximum will only tune that circuit to the same off-center frequency as the secondary!

To provide for tuning the discriminator primary, Motorola receivers incorporate a meter circuit which reads the amount of rectified current in the discriminator. This meter position is designated #5 in most receivers.

As the primary is tuned to resonance at the center frequency, the voltage applied to the secondary increases and the meter reads maximum. It is essential that a short piece of wire be temporarily connected directly across the secondary winding terminals during this adjustment in order to prevent any interaction between the windings.

Figure 2 suggests a maximum reading of -12 to -16 for this meter position, and, due to the saturation of the last limiters, this reading will be about the same for either noise or regular transmissions.

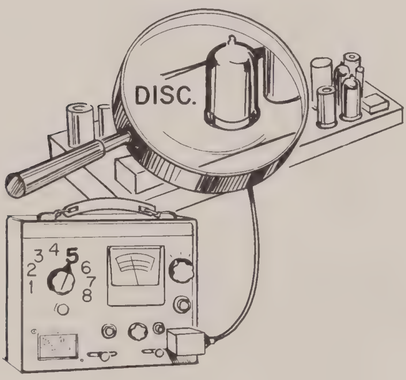
After the primary has been adjusted to maximum, the wire across the secondary is removed and the meter switch is placed in



In Switch Position 4 the Motorola Test Set Indicates the Discriminator Output.

position 4. With the center frequency applied, the secondary is tuned for a zero reading.

This zero reading must be a very sharp indication between positive and negative peaks. That is, the meter reading should rise sharply, positive and negative, on either side of zero. If these peak indications are not present the tuning is not correct or there is something wrong in the receiver circuits.



In Switch Position 5 the Motorola Test Set Indicates the Input to the Discriminator.

Oscillator Frequency Adjustment

The adjustment of the high-frequency oscillator to its correct frequency requires a source of RF signal at the exact channel frequency. Unless the RF frequency is correct, the oscillator frequency adjustment can result only in off-channel operation.

Thus, before making such frequency adjustments at the receiver it is well to first determine that the RF source is at the channel frequency. This done, the next step is to check the discriminator secondary.

Assuming the discriminator is on frequency, the frequency adjustment of the high-frequency oscillator is relatively simple. Apply the RF signal to the antenna input and view the meter indication on position 4. If the reading is not zero, adjust the oscillator frequency control for zero. Again, the zero indication at position 4 must be a sharp null between positive and negative peaks as the oscillator frequency control is varied through the correct setting.

If the local oscillator and discriminator are both off frequency, it becomes necessary to first align the discriminator to zero at the last IF frequency. In most receivers this is 455 kc, and requires a known source of signal at this frequency. Once the discriminator has been aligned, the oscillator frequency is adjusted as before.

Alignment of The Last IF Section

Where a fixed tuned filter such as the Motorola Permakay is used, for best results the last IF section and discriminator must be aligned to the center frequency of the filter band-pass. With the filter operating at a center frequency of 455 kc, the IF amplifiers and the discriminator must be tuned to the same frequency and this requires a signal of 455 kc.

The Motorola test set (P8501) mentioned earlier in this lesson can be used to supply the 455 kc signal. This test set incorporates a signal generator, its frequency being controlled by a 455 kc crystal. This fixed frequency insures proper alignment of the discriminator and IF circuits. (The test set can be used to meter the various receiver circuits at the same time it is being operated as a signal generator.)

With the meter on position 1 or 2, the plate circuits of the first two stages of the last IF section are tuned for maximum indication. With the meter in position 2, the plate of the last amplifier is tuned for maximum. For these adjustments, the signal is injected into the grid of the first amplifier stage.

The meter switch is next turned to position 5. With a short across the secondary, the primary of the discriminator transformer is tuned for maximum. The short is then removed from the secondary and, with the meter switch in position 4, the secondary is tuned for zero.

Besides the adjustments of the discriminator transformer already mentioned, it is important to check its operation under normal signal conditions; while the discriminator may be tuned to the exact center frequency, it may still fail to operate properly in the presence of an incoming signal.

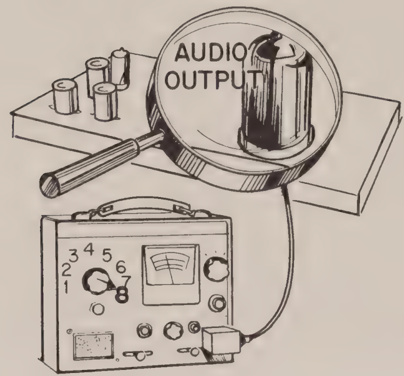
A more accurate check may be made by varying the frequency the same amount above and below the center frequency and observing the discriminator output. The amount of output should be the same (or within a reasonable balance) for equal deviations. Again the test set is convenient for this use.

For a deviation of 15 kc, crystals of 440 kc and 470 kc are alternately substituted for the 455 kc crystal in the test set and the readings in position 4 are noted. Of course the readings will be of opposite polarity, but a switch on the test set readily takes care of this condition. When the readings at 15 kc above and 15 kc below the center frequency are reasonably close, the discriminator will operate properly. If, however, one reading is considerably higher than the other we may expect the output to be distorted. Defective components as well as mistuned circuits may cause this condition.

Audio Output

In position 8, the test set indicates the amount of signal or noise at the receiver output. A speaker in the test set is connected to the secondary of the receiver's output transformer, and the voltage applied to the speaker is rectified and applied to the meter.

No attempt is made to calibrate the reading on the meter. By indicating the relative amount of signal or noise at the output, however, this reading is very convenient in making sensitivity and other checks of the receiver.



In Switch Position 8 the Motorola Test Set Indicates the Signal (or Noise) Voltage at the Speaker.

Supply Voltages

In some Motorola receivers, it is possible to use the Motorola test set to measure the B voltage available from the power supply. The test set includes the necessary circuitry to indicate this voltage when the switch is in position 7.

In this position, a series multiplier resistor makes the test set a 1000-volt DC meter---this applies to both the receiver and transmitter. The average B voltage at the receiver is between 180 and 200 volts, although some power supplies may have lower values. Whether or not a particular receiver will give an indication depends upon the internal wiring of the receiver. In order to indicate the B voltage, there must be a connection to the proper terminal of the meter socket. This connection to the proper terminal is not present in all receivers.

In our discussion of supply voltages, some consideration must be given to the A voltage (primary supply) as well as to the B voltage.

Although the test set does not measure the filament and heater voltage at the receiver, this voltage may be measured at the transmitter. (It is very simple to transfer the test set to the transmitter.) We shall speak more of this when we discuss the meter in the transmitter and when we study the test set in detail.

450-MC Receivers

While the average high-band and low-band receiver has many circuits which must be tuned to resonance, there are still others in the 450-mc receiver which require attention. These important circuits are in the multiplier stages, between the oscillator and first mixer. The receiver sensitivity depends upon the voltage applied from the oscillator-multiplier section to the mixer; hence, it is essential to provide a convenient but accurate method of adjusting these circuits to resonance.

The low operating frequency of the oscillator makes it necessary to use one or more stages of frequency multiplication in order to provide the proper signal to the mixer. It is not always possible to adjust the multipliers for resonance by watching the reading at the limiters, because the output of the multiplier section to the mixer may be low if the tuned circuits are far from resonance (the limiter reading due to an IF sig-

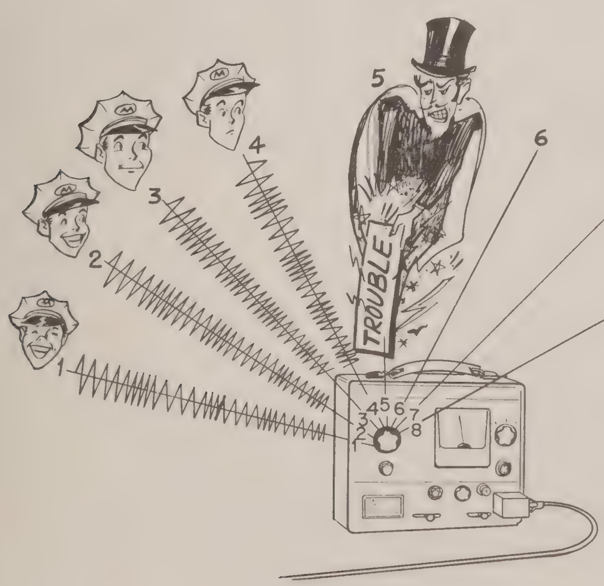
nal may be zero). A more positive method of tuning these multipliers must be found.

Because the multipliers are operated in class C (in order to provide a high output at the harmonic frequencies), the strength of the signal determines the amount of grid-leak bias. By measuring the grid current, then, an accurate indication of the RF level is realized. The necessary resistors and capacitors are included and connections are made to terminal of the meter plug.

A problem is encountered here, for there are no "free" terminals on the plug leading to the meter switching circuit. A convenient solution is to use an adaptor cable, installed between the meter and the receiver chassis. The multiplier grid circuits are now monitored in meter switch positions 4 and 5. Thus, with the adaptor cable installed, the multiplier stages of the 450-mc receiver are tuned for maximum by observing meter positions 4 and 5. For any particular receiver it is best to follow the specific alignment procedures as found in the instruction manual for that receiver.

Localizing Trouble by Using Meter Readings

Here is an example of how the intelligent interpretation of meter readings can be used to simplify



"Trouble" in the Two-Way Receiver can Usually be Pinpointed by the Readings of the Various Receiver Circuits.

service work. Suppose a receiver is "dead". No perceptible sound comes from the speaker, regardless of the settings of the squelch and volume controls. After making sure that the tubes are lit, the next procedure is to connect the test set to the receiver and observe the readings for all positions indicated in figure 1. Nearly normal readings in position 1, 2 and 6 immediately tell us that the circuits up to the limiters are probably working ok; we can momentarily eliminate them as a probable source of trouble.

The discriminator readings (4 and 5) are next observed. If they are not correct we immediately know that the trouble is between the first limiter and the discriminator. If, on the other hand, the discriminator readings seem normal, the fault is then in the squelch or audio circuits.

Additional elaborations may be made from the readings secured on the meters, but it is not the purpose of this assignment to present a complete trouble shooting procedure. The important point is that the meter plays a very prominent part not only in the alignment of the receiver, but in isolating all kinds of troubles and even pin pointing them to a particular section or circuit within the receiver. To paraphrase a popular saying, "the meter is the best friend a serviceman could possibly have."

Motorola has two test sets, the P8501 and the TU 546. This lesson describes the meter positions of the P8501 unit. The newer TU 546 test set has the same metering system, although all the switch positions may not be identical. Regardless of the test set used, the system and application remains the same. A later lesson describes both units in detail.

STUDENT NOTES

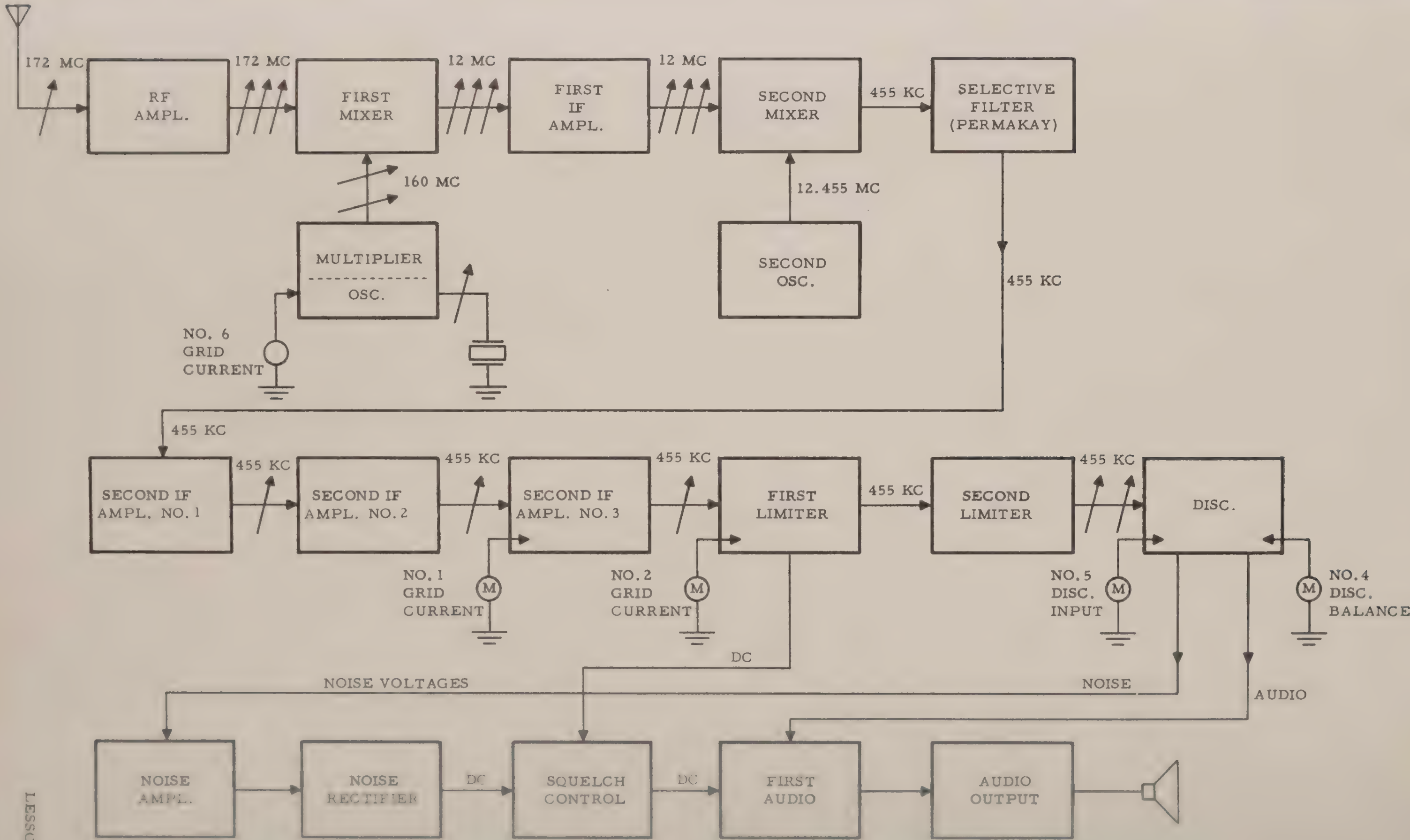

172 MC
RF AMPL.
172 MC
FIRST MIXER
12 MC
FIRST IF AMPL.
12 MC
SECOND MIXER
455 KC
SELECTIVE FILTER (PERMAKAY)
160 MC
MULTIPLIER
OSC.
12.455 MC
SECOND OSC.
455 KC
NO. 6 GRID CURRENT
455 KC
SECOND IF AMPL. NO. 1
455 KC
SECOND IF AMPL. NO. 2
455 KC
SECOND IF AMPL. NO. 3
455 KC
FIRST LIMITER
455 KC
SECOND LIMITER
455 KC
DISC.
NO. 1 GRID CURRENT
NO. 2 GRID CURRENT
NO. 5 DISC. INPUT
NO. 4 DISC. BALANCE
DC
NOISE VOLTAGES
NOISE
AUDIO
NOISE AMPL.
NOISE RECTIFIER
DC
SQUELCH CONTROL
DC
FIRST AUDIO
AUDIO OUTPUT

FIGURE 1.

Switch Position	Circuit Location	Indicates	Average Indication	Usually Reads
#1	Grid of Last IF Amplifier	Grid Current Due to Signal or Noise	-0.1 to -1.0	Maximum
#2	Grid of First Limiter	Grid Current Due to Signal or Noise	-18 to -40	Maximum
#4	Discriminator Output	Discriminator Balance	0	0
#5	Rectified Current in Discriminator	Strength of Signal Applied	-12 to -16	Maximum
#6	Grid Current of Oscillator	Oscillator Activity	-12 to -40	Maximum
#8	Audio Output	Voltage at Speaker	Varies with Modulation	

Figure 2

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Name ______________________________ Student No. ______

Street ________________ Zone ____ Date ______

City ______________ State ________ Grade ______

EXAMINATION LESSON RA-9

1. Besides using various meter readings for trouble shooting a receiver, the serviceman uses these readings ________________

2. Meters are often used in receivers to record grid current due to limiting action. This grid current is caused only by signals of the receiver operating frequency, and will be zero without a signal. TRUE ________ FALSE ________

3. Referring to Figure 1 of the lesson, the meter of position #6 shows zero current, but the filament and plate supply voltages are correct. The trouble is likely to be in the ________________ stage.

4. With an unmodulated signal of the receiver operating frequency applied, as the oscillator grid circuit is tuned from "off" resonance to resonance, the reading of meter position 2 will probably (increase)(decrease).

5. A receiver is being aligned by observing the meter readings in position 2. Half-way through the procedure, the meter reading no longer shows any change as the front-end circuits are tuned. The probable trouble is ________________.

   As a remedy, we may either ________________
   or ________________.

6. While observing meter position 4, which of the following are adjusted at some time or another in the tuning of a receiver?

   A. Discriminator primary. ________
   B. Discriminator secondary. ________
   C. RF circuits ________
   D. Oscillator frequency ________
   E. Oscillator grid circuit ________

7. In order to tune the primary of the discriminator transformer to exact resonance, it is desirable to prevent any interaction between the transformer windings. This may be accomplished by ________________.

8. After each of the following, indicate the number of the metering switch position that may be used to adjust the circuit.

   A. Oscillator frequency ________
   B. Discriminator primary ________
   C. Oscillator grid tank ________
   D. Discriminator secondary ________
   E. Oscillator multiplier ________

9. Referring to figure 1 at the lesson, meter #1 shows a normal reading, but meter #2 shows no reading. What specific trouble(s) would you anticipate? ________________

10. Using Figure 1 of the lesson, analyze the following meter readings found for a receiver and indicate that stage or stages of the receiver in which you would anticipate trouble.
    Meter positions 1 and 2, normal; Meter positions 4 and 5, zero; Meter position 6, -30.
    The trouble is in ________________.

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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-10
FM RECEIVERS

Receiver Specifications

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON RA-10
FM RECEIVERS

Receiver Specifications

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

RECEIVER SPECIFICATIONS
LESSON RA-10

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Two-Way Radio in the cab of an overhead crane represents but one of the places you'll find this versatile working tool in industrial and manufacturing plants — and you'll also hear how it can boost productivity by 10-20% — even up to 50% by better coordination of men, machines and materials.

RECEIVER SPECIFICATIONS

Lesson RA-10

Why "Specs" Are Important

The receivers of a two-way communications system, which have been performing well in their particular service, suddenly begin to pick up signals and interference from another system. Furthermore, these transmissions are continuous, being picked up as regularly as the signals of its own transmitters.

An investigation reveals that the interference comes from a local two-way system just placed into operation on a channel close to the operating frequency of the receivers.

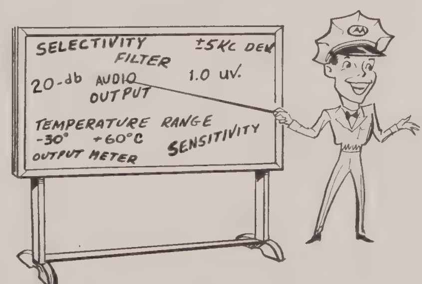
The specifications---generally called "specs"---indicate that the receivers' selectivity is not adequate to reject transmissions on adjacent or alternate channels. Thus, the receivers are performing "as well as can be expected"; they just do not have enough selectivity to reject the interfering signals.

From the service viewpoint, the technician must realize that all receivers are not alike. For example, some receivers are designed for operation where there are signals in the adjacent and alternate channels---others are not.

In order for the serviceman to predict whether a receiver will provide normal service in any given application, he must be able to interpret the specs for that receiver and determine its intended use. With this thought in mind, we shall discuss in this lesson the more important receiver specifications and considerations. Because we have already mentioned selectivity, we shall start with this particular spec.

Selectivity

In modern applications of the communications receiver for mobile operation, selectivity is becoming increasingly important.



The Successful Service Technician is Well Acquainted with Receiver Specifications.

Because of the wide variety of uses being made of such equipment, it is important for the receiver to have the correct selectivity characteristics for each application. By interpreting the selectivity specs for a particular receiver, we can determine its recommended system operation.

Table 1 gives the specs of a Motorola receiver which is intended for operation within the 25-54 mc range. Three models, having the suffixes S, X, and W, are available. These models are basically the same except for the Permakay filter used. (In our discussion of Motorola's Permakay filter, we said different models of filters made it possible to equip the receiver with any required degree of selectivity.) The selectivity and use of these receiver models are given in the first three lines of table 1.

The S model is to be used in systems having a 5-kc deviation and a channel spacing of 20 kc. (This is also evident from the selectivity column.) The "-100 db attenuation at 18 kc" indicates adjacent channel application--this model is designed to operate with a minimum deviation and with close channel spacing. This receiver, however, will not give good results when used in a system having a 15-kc deviation. Its highly selective Permakay filter will accept only a narrow band of frequencies and much of the modulation energy (deviations) will not get through to the discriminator. Thus, the output from the receiver will be both weak and distorted.

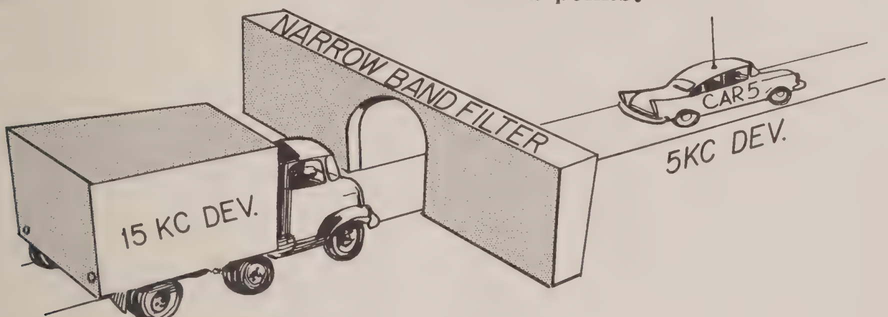
The X model, on the other hand, uses a filter with comparatively little selectivity; the attenuation is 100 db down at 120 kc. This receiver could never produce good results in adjacent channel applications. Signals on adjacent channels receive comparatively little attenuation in the filter of this receiver and they will be reproduced in the speaker or, at least, will interfere with the desired signals.

The S and X models represent the limits of selectivity likely to be encountered in modern two-way communications receivers, most of which have a selectivity somewhere between these values. The W model receiver (table 1) has a designed deviation acceptance of 15 kc and, with an attenuation of 100 db at ± 32 kc, this receiver is suitable for adjacent channel operation, where the channel spacings are 40 kc.

Although an attenuation of 80 or 90 db is considered adequate in most applications, 100 db (as used in table 1) provides even better protection from interference. This attenuation, which represents a voltage ratio of 100,000, is sufficient to reject unwanted signals that may be present. When the rejection is as high as 100 db, only those interfering signals which are of unusually high amplitude are likely to have any effect on the receiver.

Although it is seldom necessary for the service technician to measure the overall selectivity of the

receiver, it is possible for him to do so without a lot of expensive test equipment. In addition to the standard signal generator, a frequency measuring device is required. The procedure is as follows.



A Receiver Having a Narrow Band Filter is Not Intended for Use in a System Employing 15KC Deviation.

Set the generator to the channel frequency of the receiver and adjust the output to the level corresponding to the rated 20-db quieting sensitivity. Note the reading on the test set at position 1 (the reading at position 2 will probably be in saturation). Next increase the generator output 100 db---100,000 times greater---and vary the generator frequency above and below center until the reading at position 1 is the same as that recorded for the channel frequency.

Measure the frequencies of these off-channel signals, using the frequency meter. It is not necessary to measure the signals at the RF level. Instead, the frequencies at the last IF may be determined, for the frequency variation at the last IF is the same as that at the receiver input. These two frequencies indicate the bandwidth of the receiver at the 100-db points. [1]

Sensitivity

While the "20-db quieting" sensitivity does not appear as a spec in some standards, it provides the quickest and most efficient method to use when servicing receivers. For this reason, receiver specifications should always include sensitivity expressed in terms of the amount of signal (in microvolts) required to produce "20 db quieting", that is, to reduce the noise coming from the speaker by 20 db. Because 20 db represents a voltage ratio of 10 to 1, it becomes a convenient means of determining the amount of noise reduction.

To make this 20-db quieting test, first place an AC volt-meter

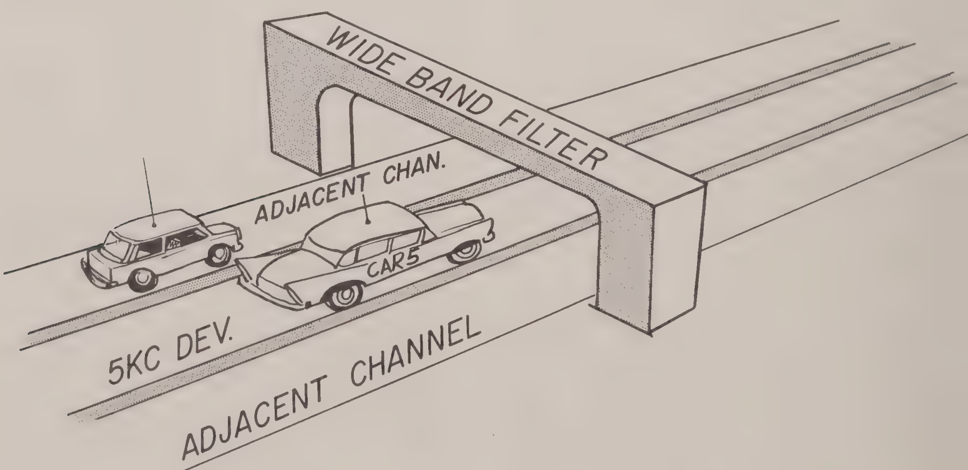
1. See "Receiver Selectivity and Sensitivity Measurements".

across the speaker voice coil, unsquelch the receiver, and adjust the noise output voltage by means of the volume control for a convenient reading on the meter, such as 0.5 volt. Now apply a signal of the channel frequency to the receiver input and gradually increase the signal level until the noise output decreases to one-tenth the original reading; this will be 0.05 volt, if the original setting was 0.5 volt. (In lieu of the AC meter, the Motorola P8501A Test Set may be used in switch position 8, to indicate the relative output at the speaker. Adjust the volume control for a reading of 10 on the meter and increase the signal level until this reading decreases to 1.)

Because the noise output, in either case, is but one-tenth its original value, the noise has been reduced 20 db. The amount of signal applied to the receiver input, as read on the calibrated output indicator of the signal generator, is the rated sensitivity of the receiver. The guaranteed sensitivity of Motorola receivers usually ranges from 0.3 mv (microvolts) for low-band receivers to 1 mv for 450-mc receivers.

The above test, of course, will be only as reliable as the accuracy of the generator output calibration. Also, for a valid measurement, the generator output impedance must match the input impedance of the receiver--50 ohms for most receivers.

The value of the test also depends upon the point where the receiver output is measured. By measuring the voltage at the voice coil, the operation of the entire receiver is taken into consideration. If the voltage at the discrim-



A Receiver Having a Wide Band Filter Will Not Reject the Adjacent Channels in Split Channel Operation.

inator output is measured, however, we still do not have an indication of what takes place at the speaker--which is what we are chiefly interested in.

When making tests for receiver sensitivity, we must remember that every method has certain shortcomings and that no method can give the final, complete picture. The actual operating selectivity and sensitivity are affected by a number of additional factors, such as desensitization, intermodulation, spurious response, squelch sensitivity and noise level.

Only the experienced engineer, using a lot of expensive test equipment, can fully evaluate the receiver and even then, the actual operation of the receiver under all conditions must be the final test of its worth.

Frequency Stability and Temperature Range

A high degree of frequency stability is one of the most important requirements of a communications receiver. The most detrimental factor to frequency stability is temperature. The relationship of frequency stability to temperature changes may be expressed in several ways. As given in table 1, for example, a certain Motorola receiver operating in the 25-54mc range has a stated frequency stability of "±750 cycles for temperature changes between -30^{o} C and $+60^{o}$ C, referenced to $+25^{o}$ C." This means that, within this temperature range, the oscillator will not vary more than 750 cycles from its frequency at 25^{o} C.

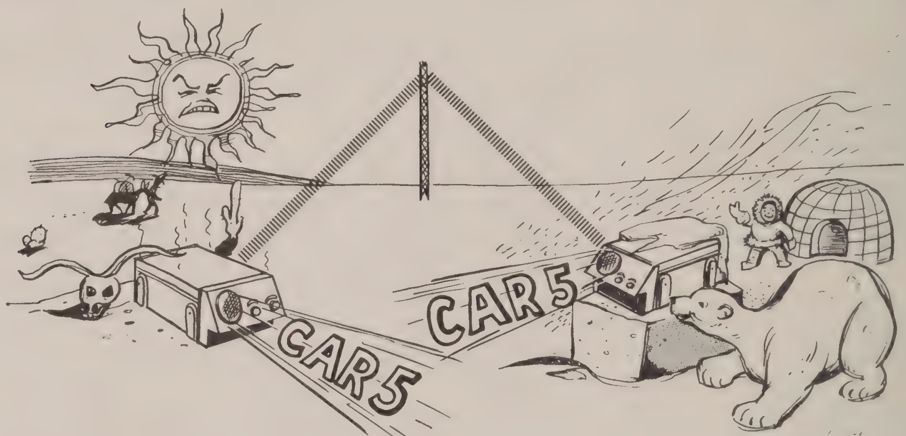
A receiver with this degree of frequency stability will undoubtedly operate well at all times. A receiver with less stability may work most of the time, but when the temperature of the equipment reaches the extreme ranges of hot and cold, reception may be poor or even nonexistent.

One late model Motorola receiver, designed for operation in the 450-470 mc band, has a stability (controlled by its AFC circuits) which is within ±0.0004 per cent of the transmitter frequency! While the crystal keeps the oscillator relatively close to the channel frequency, the action of the AFC circuit is used to swing the oscillator still nearer to the correct frequency, thus providing positive reception under the most adverse conditions.

A stability of 0.0004 per cent at this frequency means that the receiver will be within 2 kc of the transmitter frequency. At 450 mc, this is sufficiently close to assure normal reception without a loss of sensitivity or any degradation in performance.

A check can be made of the frequency stability of a receiver if we know the amount of voltage produced at the discriminator output for a given change of carrier frequency. It is not necessary, from a practical standpoint, to check the discriminator output for

all values of frequency variation. We can assume that, within a reasonable range, the discriminator output will be linear. That is, if a 15-volt output is produced by a change of 15 kc, 1 volt represents a variation of 1 kc, 5 volts means a 5-kc deviation, etc.



A Receiver with Good Frequency Stability will Work Equally Well when Hot or Cold.

By installing crystals of 440 and 470 kc in the test set and measuring the discriminator voltages, we can obtain an immediate calibration of the discriminator response. We can normally expect, as a minimum, a 15-volt output for a 15-kc deviation, and for convenience we will assume that the receiver being tested produces an output of exactly 15 volts for input signals of either 440 or 470 kc (±15-kc variation).

We are now ready to check the frequency stability of the receiver. First, apply a signal of the channel frequency to the receiver input and adjust the local oscillator frequency for a zero discriminator output. Now, if the applied signal has a constant frequency, any change in the high-frequency oscillator will produce a change in the discriminator output. For example, if the oscillator signal which is applied to the mixer changes 1 kc, the first and second IF frequencies of the receiver will also change 1 kc. This 1-kc change in the last IF will cause a 1-volt variation in the discriminator output.

By means of this procedure, it is possible to determine (1) the degree of frequency variation under extreme conditions of hot and cold weather operation, (2) the frequency drift over a long period of time, or (3) how long a warm-up period is required for the receiver to reach the correct operating frequency. The accuracy of this test, however, is limited by the stability of the RF signal source, for any shift of the ap-

plied RF will cause a corresponding change in the discriminator reading. Therefore, it is essential to provide a test signal of extremely high stability.

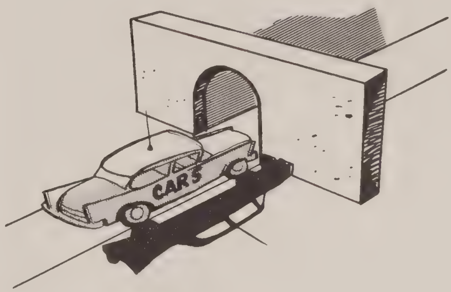
Spurious and Image Frequency Response

Most Motorola receivers have ratings of more than 100-db attenuation of all spurious response, including the image frequency. Because of higher power ratings of transmitters and the crowding of more and more signals into the same area, the problem has lately become more acute, and the ability of a receiver to reject these unwanted responses often determines the difference between poor performance and successful operation.

A rejection of more than 100 db for all spurious responses insures good reception even in the most overcrowded metropolitan areas. In only a few instances has this problem been such as to require different frequency assignments or relocation of antennas. On high-frequency bands such as 450-470 mc, where channel assignments are farther apart and transmissions are not as powerful, rejections of 80 or 85 db are usually satisfactory.

Squelch Sensitivity

In the preceding lesson we saw how the squelch, to some degree, determines the receiver sensitivity; the receiver cannot reproduce a message unless the squelch is open. Squelch sensitivity must therefore be better than receiver sensitivity; the squelch must open for signal inputs which are even lower than the stated "20-db quieting" sensitivity of the receiver. The squelch should be open when the signal reaches a level producing 3-4 db of quieting. The guaranteed squelch sensitivity of most Motorola receivers ranges between 0.1 and 0.3 uv.

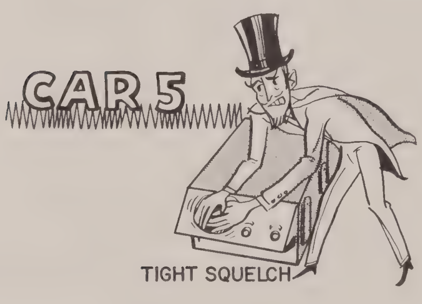


The Receiver Tuned Circuits Must Reject the "Image" and Other Undesired Signals.

Squelch sensitivity can be ascertained by checking the first audio stage (or by listening to the speaker) and determining at what value of signal input the audio tube is unbiased. For this check, the squelch control must first be adjusted to the point where the noise in the speaker is just quieted. Any additional advance of the squelch adjustment increases the amount of signal needed to open the squelch, thus lowering the threshold squelch sensitivity.

Audio Ratings

While the audio system of a communications receiver does not require the fidelity of a "hi-fi" system, it should have good response at the voice frequencies (300-3000 cps) if messages are to be intelligible. In order to restore these voice frequencies to their original balance, the FM receiver must have a deemphasis network rated at "6 db per octave." This means that, where one frequency is twice as high as another, the higher frequency must be 6 db down in the receiver response.



A "Tight" Squelch Adjustment Makes the Receiver Insensitive to Weak Signals.

The audio power output for the receiver of figure 1 is 2 watts with less than 10 per cent distortion. This power is delivered to a 3-ohm voice coil. Other receivers may have different audio power ratings, depending upon the particular requirements of the service in which they are to be used.

Antenna Considerations

An antenna is considered to have the same characteristics when it is used with a receiver as it has when used with a transmitter; power gain, directivity, and similar factors apply in both cases. The antenna and transmission line must match the input impedance of the receiver as well as the output impedance of the transmitter if the same antenna is used for both, which is usually the case in two-way communications.

Without a match between the antenna system and the receiver, it is impossible to transfer maximum energy to the receiver input. A 50-ohm impedance is most common for transmitter outputs, receiver inputs, transmission lines and antennas.

Reserve Performance

The rated sensitivity of a receiver may be conservatively stated by the manufacturer or it may refer to the maximum sensitivity attainable by the receiver. In the latter case, the receiver will operate with the specified sensitivity only when the tubes are up to maximum gain and when the circuits are peaked to their maximum settings. Such a receiver can be expected to have a somewhat lower sensitivity in actual use.

As soon as the tubes or other components show their first signs of aging, the sensitivity of the

receiver is noticeably lower and when the circuits change from their maximum settings (due to vibration or changes of temperature and humidity), the receiver performance is somewhat less than maximum. Considerable--and almost continuous--servicing is required in order to maintain the system at maximum operating efficiency. We say that such a receiver shows very little "reserve performance."

Reserve performance is most evident when the given receiver specifications are not the maximum attainable, but are the average that may be expected from the unit. As an example, a receiver may have a specified sensitivity of 0.5 microvolt, but with selected tubes and with every circuit on exact frequency the sensitivity may be considerably better (lower) than this figure. Then, when normal aging of the tubes takes place, or if a circuit or two is not on exact frequency, the receiver will still operate with its stated sensitivity.

Any large amount of reserve performance is difficult to build into the front end of the modern receiver and here is where system reserve becomes important. Where the signals available and the power outputs of the various pieces of equipment are supplying signals just sufficient to maintain contact, any degradation will affect the normal functioning of the system.

Any appreciable decrease in amplification of the front-end stages will usually cause some loss in performance. The gain of these stages is kept low in order to minimize the likelihood of spurious response, intermodulation and desensitization.

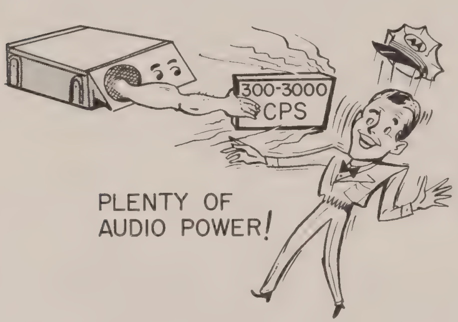
A good reserve, however, can be built into the last IF section of the receiver. Then, when tubes undergo normal aging, top performance can still be obtained. Such a receiver is said to have good "reserve".

Effects of Temperature and Humidity

During times of emergency, other systems of communications are sometimes disrupted and two-way equipment is often the only means of communication available. It then becomes vitally important for this equipment to operate under all conditions of heat, cold, and rain. It is also desirable that when the equipment gets wet but eventually dries out and is returned to service, it operates as well as it did originally.

Extremes of temperature and humidity often reduce the sensitivity of the most carefully designed equipment, resulting in changes in the operational characteristics of different components within the receiver. The use of units which are least affected by these factors is an important consideration in connection with any two-way equipment.

One of the first effects noticed at low temperatures is the reduction of capacitance of electrolytic capacitors. At zero degrees F, the capacitance may be too low to prevent a hum from being heard in the speaker. Certain types of bypass capacitors, too, lose their capacitance at lower temperatures, resulting in instability and loss of gain.



A Full Quota of Audio Power from the Speaker Assures Readability of the Message.

Paper capacitors are particularly susceptible to continued moisture and they gradually develop leakage resistance. Mobile communications receivers must use other types of capacitors that are sealed from the effects of moisture.

Temperature compensating capacitors are often used in circuits which are frequency sensitive to temperature. When these units are used, the tuned circuits maintain a more constant resonant frequency with changes of temperature.

The above examples illustrate the importance of using material least affected by changes of temperature and humidity. Selection of proper material is economical, too, in that such equipment continues to operate over a longer period of time.

Receiver Construction; Replacements

Aside from their specified electrical characteristics and their ability to withstand reasonable changes in temperature and humidity, the various units and component parts used in a communications receiver must always exhibit sturdy mechanical properties, and they must be properly placed (or replaced), securely mounted, and adequately shielded where the occasion requires it. These considerations become important factors toward maintaining continuous, trouble-free operation of any receiver. They are particularly important in the case of two-way communications receivers.

Severe jarring or continuous vibration of the chassis can cause the parts to shift position if they are not mechanically sturdy and properly mounted. A shift in position of parts or wiring may detune the circuits or allow interaction between circuits that should be isolated from each other. Under severe strain, the leads of a resistor or capacitor may pull loose from the unit. In exaggerated cases of vibration and shock, variable capacitors or coil tuning

slugs may be jarred out of position; transformers and other heavy units may even break loose from their mountings.

Closely associated with the subject of parts placement is the shielding required between certain circuits, particularly in the case of the oscillator and its multipliers. Currents (at either the oscillator fundamental or any of the unused harmonics) can cause spurious response if they are allowed to enter the RF, IF, or mixer circuits of the receiver. These sections are usually shielded, both magnetically and electrically, and located so that they are physically isolated from the rest of the receiver.

All these factors must be kept in mind by the serviceman when he is either servicing the equipment or making replacements. The importance of the exact position of parts in the front end of the receiver cannot be overstressed. The serviceman must be very careful in probing around this section, so that he does not change this arrangement. When making any replacements, he should first make a sketch of each component (mentally at least), so that when he is finished, each component and wire is in the same position it occupied originally.

When making any replacement, all the characteristics of the replacement unit or part must be exactly the same as those of the original. This rule applies particularly to capacitors, where it is seldom enough to merely use a replacement unit having the same voltage and capacitance ratings. The replacement must be one recommended by the manufacturer of the equipment, and this usually means it must be an exact duplicate of the original. It must conform to all specifications.

Obsolescence and Flexibility

Obsolescent equipment is equipment which is tending to become out of date. A receiver may be just as good as it ever was, but changing times and conditions require certain modifications to be made if it is to continue operating with maximum efficiency in the face of new frequency allocations, for example, or changes in service requirements. Thus, standards which are set up for today's equipment may undergo radical changes within a few months or a year from now, and this applies particularly to frequency assignments within a band.

An example of this situation was given at the beginning of this lesson. Equipment designed for alternate channel operation (with no transmissions on adjacent channels) does not require a high degree of selectivity. It is not uncommon, however, for this situation to change. After a time, adjacent channel assignments are often made in the same area. Unless the equipment can be adapted to this new operation, severe interference problems arise. The equipment has now become obsolete.

Another example of obsolescence is seen when equipment designed to be operated from a 6-volt battery and ignition system is to be used on a 12-volt system.

Both of these tendencies toward obsolescence have been overcome in Motorola equipment. Since the selectivity in Motorola receivers is determined by the Permakay filter, all that need be done in the first example is to change to a more selective filter; the receiver is then ready to operate successfully under the new conditions.

In the matter of primary power changes, Motorola has devised a method which permits the same equipment to be used on either 6 volts or 12 volts. This method, which is more fully discussed in the section on power supplies, makes use of a special power cable and fuse which can be readily installed in any mobile equipment. (Conversely, this equipment can be changed back just as easily, from 12 volts to 6 volts.)

While the latter example concerns flexibility rather than obsolescence, it illustrates the interrelationship of the two--the more flexible is the equipment, the less it tends to become obsolete.

Mounting The Receiver

While the mobile receiver is packaged as a single unit, the complete communications installation consists of three units--the receiver, the transmitter, and the power supply. These three units are built on separate chassis but combined into one complete assembly within a single housing.

In some installations, the receiver, transmitter and power supply are trunk mounted, with the speaker, microphone and operating controls contained in a control head, mounted near the driver. Or, the entire equipment may be built into a single compact unit and mounted near the driver.

In any type of installation, the housing containing the equipment should itself be firmly mounted. In extreme cases, the housing may be shock mounted in order to avoid excessive vibration of the equipment.

Conclusion

This lesson on specifications concludes the receiver section of the training. (Receiver service problems will be taken up in later assignments.) The next section is devoted primarily to the study of transmitters. The transmitter lessons follow the same general arrangement that was used in the receiver section. Starting with an overall block diagram, the entire transmitter is discussed in the first lesson in order to show its relationship to the receiver and the interrelationship of its various stages. These individual stages--oscillator, phase modulator, multipliers, etc.--are then considered separately and studied in detail, as in the receiver section.

STUDENT NOTES

TABLE 1

RECEIVER SPECIFICATIONS -- FREQ. = 25 to 54 MC.

MODELS	TA111B-S	TA111B-W	TA111-X
CHANNEL SPACING	20 kc.	40 kc.	120 kc.
SELECTIVITY	-100 db @ ±18 kc.	-100 db @ ±32 kc.	-100 db @ ±120 kc.
MODULATION ACCEPTANCE	±5 kc.	±15 kc.	±15 kc.
SENSITIVITY	Less than 0.35 microvolt for 20 db quieting; 50 ohms rf input impedance		
FREQ. STABILITY	±750 cps of center -30° to +60° C., +25° C reference		
SPURIOUS AND IMAGE REJ.	More than 100 db		
SQUELCH	Noise comp, adjustable, threshold sensitivity of .1 microvolt		
AUDIO OUTPUT	2 watts to 3 ohm v.c. less than 10% distortion		
AUDIO REPSONSE	+1, -8 db of 6 db/octave deëmphasis, 300-3000 cps.		

FIGURE 1

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Name ________________________ Student No. _____

Street _________________ Zone ____ Date _____

City _______________ State ________ Grade _____

EXAMINATION LESSON RA-10

1. The selectivity of a receiver is rated "60 db down at 40 kc". This receiver is operated in an area having unusually strong signals on the adjacent channels, which are spaced 40 kc from the operating frequency. This receiver (will)(will not) be able to reject the adjacent channel signals.

2. A Motorola receiver designed for 5-kc deviation operation is used in a 15-kc deviation system. The receiver output will be: (check correct answers).

   Loud ________ Weak ________ Normal ________ Distorted ________

3. When the various receivers in a complete system were monitored continuously, it was noted that the reading on position 4 would vary slightly from one transmitter to the next. Two things could cause this effect. (1) ________________
(2) ________________.

4. A particular Motorola receiver originally intended for wide band operation must now have greater selectivity, due to additional systems being placed on the adjacent channels. The most practical approach to acquire the greater selectivity is to replace ________________.

5. Without a signal applied to the receiver, the squelch is opened and the volume adjusted for a meter reading of 1 volt AC at the output. An unmodulated RF, applied to the input, is increased in amplitude until 20 db of quieting is realized. The meter reading will now be ________________

6. The squelch sensitivity of a receiver changes from 0.3 to 1.0 uv due to some defect within the squelch circuit. The weakest signal that will now be heard is:

   0.3 uv. ________ 1.3 uv. ________ 1 uv. ________ 0.7 uv. ________

7. The stability of the oscillator in a communications receiver is given as 0.0005%. The operating frequency of the oscillator is 155.0 mc at a temperature of $+25^{\circ}C$. This oscillator should not swing higher than ________ mc, or lower than ________ mc.

8. In measuring the power output of a receiver, the maximum voltage produced at the 3-ohm voice coil is 2.5 volts. The power output is ________ watts. SUGGESTION: use the formula W equals E^2 divided by R.

9. The guaranteed 20-db quieting sensitivity of a receiver is 0.4 uv. This means that a signal of 0.4 uv or greater will cause ________________
________________ at the receiver output.

10. A generator is to be used to measure the sensitivity of a receiver. The rated receiver input impedance is 50 ohms. The output impedance of the generator is 50 ohms. Will the results be valid? Yes ________
No ________

national

MOTOROLA

RADIO COMMUNICATIONS

service

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-1
FM TRANSMITTERS

FM Transmitters
Block Diagram Analysis

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-1
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FM Transmitters
Block Diagram Analysis

—one of a series of lessons on two-way FM communications—

MOTOROLA **TRAINING INSTITUTE**
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
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DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

FM TRANSMITTER

BLOCK DIAGRAM ANALYSIS

LESSON TA-1

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

The new Business Radio Service is one reason why antenna towers are sprouting from any and all types of commercial organizations such as this nursery.

FM TRANSMITTER

BLOCK DIAGRAM ANALYSIS

Lesson TA-1

Basic Concepts

A communications system, we have learned, includes a transmitter, a transmission medium, and a receiver. In the receiver section just concluded, we started with an overall block diagram, then proceeded to study the various stages of the communications receiver. The same procedure will be followed as we learn about transmitters. The study of transmitters, however, requires a different approach, for the purpose of the transmitter in the communications system is quite different from that of the receiver. It is important to appreceiate this difference before continuing.

In the receiver, we started with an incoming signal picked up by the antenna. This signal was processed inside the receiver, resulting in the reproduction of the message in the speaker. The transmitter, on the other hand, starts with the spoken message (and the RF produced by the oscillator) and produces the frequency modulated RF signal which is radiated from the transmitting antenna.

With this concept in mind, let us analyze the overall block diagram of the FM transmitter. First, however, we must understand the various types of modulation which produce an FM wave.

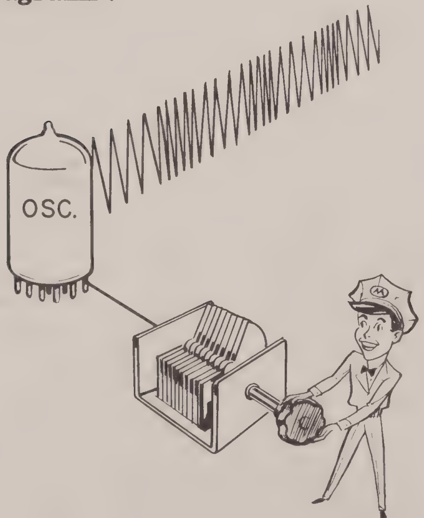
Types of Modulation

The distinction between frequency modulation and amplitude modulation consists generally in the manner of combining the audio with the carrier, and the nature of the wave thus produced. When the modulation signal causes changes in the RF amplitude we have amplitude modulation. When the audio signal produces variations in the RF frequency, the system is known as frequency modulation. These two types of modulation were discussed in the first lesson of the receiver section.

A third method of modulation produces variations in the phase of the RF carrier. The wave is then said to be "phase modulated" (abbreviated PM) rather than frequency modulated. Because the phase-modulated wave has the same characteristics as a frequency-modulated wave which has been preemphasized, however, we consider the output of the phase-modulated transmitter as being FM. The only difference is in

the method of producing the wave, and the receiver operates equally well for either preemphasized FM waves or waves produced by a phase-modulated system. [1]

In the transmitter, however, phase modulation is of considerable importance. The deviation characteristics of the PM wave differ from those of FM and the technician of serviceman should be able to recognize the difference between the different systems of modulation. How do these two systems differ from each other when they are represented by block diagrams?



In the Direct FM Transmitter, Modulation is Introduced at the Oscillator.

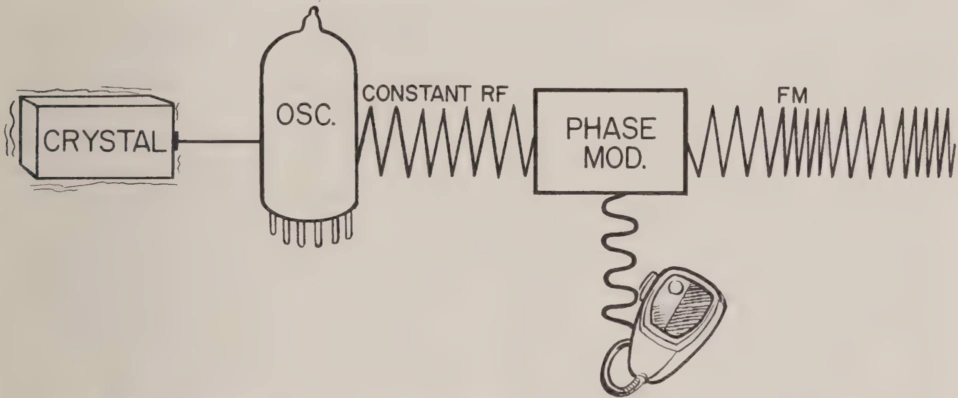
Frequency Modulation vs Phase Modulation

While the block diagram of the basic FM transmitter (figure 1) resembles that of the basic PM transmitter (figure 2), the major difference is apparent where the audio is combined with the RF ---where modulation takes place. In the FM transmitter, the modulation signal is applied directly to the oscillator (usually not crystal controlled); in the phase-modulated transmitter, it is introduced at the stage following a crystal controlled oscillator.

The circuitry of figure 1 is characteristic of FM transmitters. The audio is applied directly to the oscillator rather than to one of the following stages. It is applied so as to vary the oscillator frequency in accordance with the audio amplitude. This system is sometimes called "direct FM" to distinguish it from FM produced by phase modulation.

In the phase-modulated transmitter of figure 2, the RF signal from the oscillator and the amplified audio from the microphone are combined in the phase modulator to produce a phase-modulated signal. Here the phase of the RF signal changes according to the audio, and this changing phase effectively produces a changing frequency. Hence, phase modulation is essentially frequency modulation. The frequency deviation which results from a phase modulator, however, does not have the same characteristics as direct FM. Instead, the PM wave contains "preemphasis". Thus it may be said that the circuit of figure 2 has modulation characteristics which are identical to those of a direct FM transmitter which includes preemphasis.

1. See TM 11-668, pages 1-10; also FM Transmission and Reception, pages 1-11.



In the Phase Modulated Transmitter the Oscillator is Crystal Controlled and Modulation Takes Place in the Following Stage.

The circuitry following the modulation section is essentially the same for both transmitters. In most FM transmitters (whether FM or PM), the oscillator operates at a frequency much lower than the assigned channel frequency and it is common to find a series of frequency multipliers following the oscillator (or phase modulator, in phase-modulated transmitters). When the frequency has been stepped up to the operating frequency of the transmitter, the signal is applied to the final or power amplifier. Here the power is increased to the desired level and the energy is then transferred to the antenna, from which it radiates into space. [2]

A phase-modulation system is used almost exclusively in FM two-way communications equipment. The block diagram of a Motorola 168-mc transmitter shown in figure 3 is typical of most mobile transmitters in use today. (This arrangement will be used as a model in the transmitter lessons which follow.) We shall now study briefly each stage of the transmitter.

The Oscillator

The basic function of the oscillator in the FM transmitter is the same as in the receiver---it acts as a generator of RF energy. Beyond this point, however, the similarity ends. The oscillators differ particularly in (1) power and (2) the disposition of the RF energy produced.

In the receiver, very little RF power is required and the amount of power generated by the oscillator is relatively small. In the transmitter, the power furnished by the oscillator must be somewhat greater. For maximum frequency stability, however, the power taken from the oscillator is kept to a minimum.

Frequency stability is important in maintaining continuous communications. Besides causing in-

2. See TM 11-668, pages 10-12; also FM Transmission and Reception, pages 21-24; also "Frequency Modulation," reference T-1.

operation in its own system, transmitter drift may interrupt communications on other channels as well. For this reason, the FCC has established certain rigid requirements relating to transmitter frequency stability. In the transmitter, the possibility of drift is minimized by putting the oscillator crystal in a thermostatically controlled oven to keep it at an even temperature at all times.

In the receiver, the oscillator output is mixed with another RF voltage, resulting in a new (IF) frequency. In the transmitter, the oscillator voltage is the only source of RF energy. Instead of being "mixed" in the next stage with another RF voltage, it is modulated by an audio voltage. After being modulated, the RF is multiplied to a higher frequency in order to establish the desired carrier.

In the communications transmitter (figure 3), the crystal maintains the oscillator at a constant frequency of 7 mc, and this 7-mc signal is applied directly to the following (phase modulator) stage without any frequency multiplication. The reason for delaying frequency multiplication until after the RF has been modulated will be evident when we study the multiplier stages. Before taking up the multipliers, let us see how the audio is applied to the phase modulator. To do this, we shall have to go back to the microphone and audio amplifier.

The Audio Amplifier

The amount of deviation produced at the phase modulator of figure 3 is determined by the applied audio signal. Because the output of the microphone is usually too low to properly modulate the carrier, an amplifier is included in order to step up the audio amplitude to the desired level.

This stage makes use of a high-gain voltage amplifier such as those found in receivers. Since the communications transmitter is employed almost exclusively for voice transmission, the audio stage is designed to furnish full amplification of the voice frequencies ranging from 300 to 3000 cps. Other frequencies are attenuated.

The Audio Clipper and Deviation Control

If the audio voltage applied to the phase modulator is too strong, it will produce excessive deviation of the transmitted signal. Excessive deviation forces some of this transmitted energy outside the intended bandwidth of transmission, resulting in interference with adjacent channel signals.

In addition, excessive deviation will degrade the message reproduced by the receiver. This results because the communications receiver is designed (for maximum selectivity) to accept only a speci-

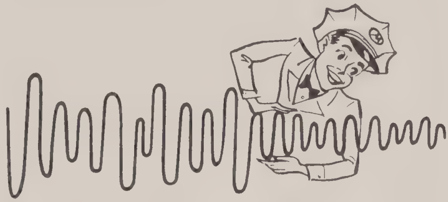
fic band of frequencies and to reject all others. If the deviation is beyond the acceptance bandwidth of the receiver, only part of the energy reaches the discriminator and the receiver output becomes both weak and distorted. This makes it doubly important to have some type of deviation control in the transmitter.

In order to limit the amount of deviation produced by the audio signal, it is necessary to control both the amplitude and the waveshape of the modulating voltage. As we shall see when we study the phase modulator in detail, the amount of deviation is determined by both the amplitude and the frequency of the audio signal. Thus, the audio section of the phase-modulated transmitter must regulate both the amplitude and the waveform of the modulating signal.

Without deviation control, the average modulation must be kept at a low level in order to prevent overdeviation by the stronger signals. As a result, the weaker audio signals produce but a small deviation. (At the receiver the reproduced message has a poor signal-to-noise ratio.)

With deviation control, it is possible to adjust the modulation so that the average voice level produces near maximum deviation of the carrier. But at the same time, the stronger audio voltages are limited, in order to keep the deviation within the prescribed limits.

At the output of the clipper stage, a volume control arrangement allows application of the desired audio signal to the modulator. This "pot" is called the IDC (instantaneous deviation control) control.[3]



In the PM Transmitter, One of the Major Requirements of the Audio Section is to Limit the Amplitude of the Modulating Wave.

Thus, while the block diagram indicates an audio clipper stage following the audio amplifier, we must realize that this stage controls the waveform as well as the amplitude of the modulating signal.

The Phase Modulator

Two separate signals, the RF from the oscillator and the audio from the clipper, are combined in the phase modulator to produce a phase-modulated wave. Because a varying phase is basically the same as a varying frequency, phase-modulation produces a type of FM wave. Since the FM is produced by means of a varying phase, this system is sometimes referred to as "indirect FM."

3. Deviation Control is considered in greater detail in lesson 4 of this series.

While the arrangement of combining two signals in the phase modulator resembles a mixer or a stage of low-level modulation as might be found in an AM transmitter, the stage is designed to hold the amplitude modulation to a very minimum; the output is FM.

When we study in detail the frequency multipliers which follow the phase modulator, we will find that multiplying the frequency also multiplies the deviation by the same amount. This means that the degree of deviation introduced at the phase modulator can be considerably less than that required at the transmitter output.

Assume that the phase modulator produces a deviation of 625 cycles. With the oscillator operating at 7 mc, the output of the phase modulator is a 7-mc RF having a deviation of ±625 cycles; the RF varies between 7,000,625 and 6,999,375 cps. Because of the relatively small amount of deviation at the modulator, the modulation linearity is excellent--- there is very little distortion. Furthermore, because the oscillator is crystal controlled, the signal has good frequency stability.[4]

The output from the modulator could be fed directly to the multipliers, but there are certain distinct advantages in feeding it first to a buffer stage. A combination of buffer and doubler is employed in the transmitter of figure 3.

Buffer-Doubler

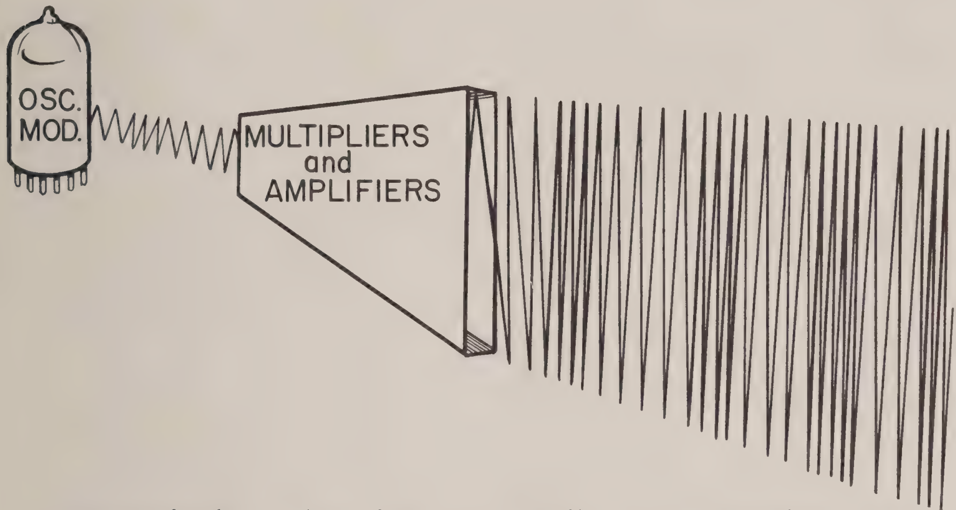
To maintain good modulation linearity, it is conventional to follow the modulator with a "buffer," so named because it acts as an isolating stage between the modulator and the multipliers.

The average RF amplifier or multiplier is a variable load on the preceding stage, tending to cause instability. Where the preceding stage happens to be the modulator, as in figure 3, this variable load would cause an objectionable degree of modulation distortion. It is the function of the buffer to act as a minimum and nearly constant load, resulting in linear deviation.

By having cathode bias on the stage, and by requiring very little driving power, the buffer-doubler

In Addition to Doubling the Frequency and Raising the Amplitude, the Doubler also causes Twice as Much Deviation in the Output Signal.

4. Phase Modulation is considered in greater detail in lesson 3 of this series.



In the Multiplier and Amplifier Stages Following the Modulator, the Amplitude, Frequency and Deviation are All Increased.

absorbs very little energy from the preceding stages. (The bias for this stage is more likely to place it in class B operation rather than in class C as is usual for most frequency multipliers.)

The doubling action is provided by tuning the plate tank to the second harmonic of the input signal. With an oscillator frequency of 7 mc, the output of the buffer-doubler is then 14 mc. While the amount of second-harmonic power available from this arrangement is comparatively low, it is not necessary to have any great amount of power at this point in the transmitter. More important is that the arrangement does not unnecessarily load the modulator to produce a nonlinear swing.

Frequency Multiplication

The doubling action which takes place in the buffer-doubler is the first of a series of frequency multiplications ending in our example in an output frequency of 168 megacycles. Transmitters usually incorporate a number of triplers and doublers for this purpose, and it might be wondered why all this multiplication could not be performed in a single stage. The reason has to do with the amount of power or "grid drive" required by the various multiplier and power amplifier stages. When it is recalled that the power dissipated in the grid circuits must be supplied by the plate circuits of the preceding stages, it can be seen that grid drive is a very important factor in circuit design and operation. Because the amount of output power available from any frequency multiplier stage decreases for the higher order of harmonics, low harmonic frequencies are generally utilized in transmitters.

One of the main advantages in using frequency multiplication in the FM transmitter is that the deviation is decreased right along with the frequency. This makes it possible to use a small amount of deviation at the modulator, and this in turn means that the modulation will be more linear.

Increasing the deviation by means of frequency multiplication does not distort the audio signal within the FM wave---it actually makes the audio component relatively that much stronger, for at the receiver the greater deviation means a stronger output voltage from the discriminator.

It is best to modulate the RF before multiplication. This allows for the greatest amount of increase after the modulator and requires only a minimum amount of deviation at the modulator. For low-band transmitters (25-54 mc band), the amount of multiplication is usually less and a greater deviation is introduced at the modulator. Conversely, 450-mc transmitters use a higher degree of frequency multiplication and the deviation at the modulator is less.

We have already assumed that the frequency multiplier increases the deviation by the same amount that the frequency is increased. In order to understand why this is so, lets look further at the action taking place within the buffer-doubler stage.

With an input signal of 7 mc and a deviation of ±625 cps, the doubler output will be 14 mc with a deviation of ±1250 cycles. The center frequency of 7 mc at the input becomes 14 mc in the doubler output, for 14 mc is the second harmonic of 7 mc. When the input varies 625 cycles above center (a frequency of 7,000,625 cps), the second harmonic frequency present in the plate circuit is 14,001,250 cps. Similarly, when the input varies 625 cycles below center (a frequency of 6,999,375 cps), the second harmonic present in the plate circuit is 13,998,750 cps. Thus, it is seen that the plate tank signal of the doubler varies in frequency between 13,998,750 cps and 14,001,250 cps, a deviation of ±1250 cps (1.25 kc).

For frequency multiplication it is necessary to have a strong harmonic content in the output waveform. This is realized by having a strong input signal and establishing class C grid-leak bias. This means the plate current exists for only a short interval during each cycle of input voltage, resulting in a high harmonic content in the plate current pulse. It is thus possible to multiply the frequency a number of times within a single stage. These principles are made use of in the tripler and other multiplier stages following the buffer-doubler.

Tripler Stage

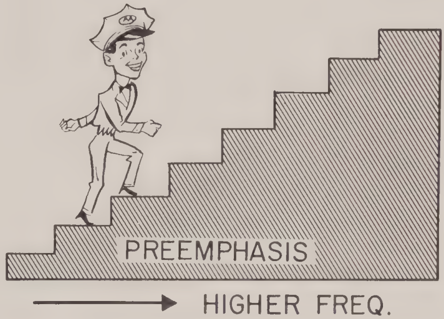
The general principles of operation of the tripler stage are the same as those of the buffer-doubler. The grid circuit is arranged

so that more power is absorbed, however, and the grid-leak bias establishes class C operation. While the plate of the preceding stage is tuned to the second harmonic frequency of the oscillator frequency, the tripler plate tank is tuned to the third harmonic of its input signal from the buffer-doubler. The output of the tripler is the sixth harmonic of the oscillator.

With the plate circuit of the tripler tuned to the third harmonic of its input signal, the output frequency --- and deviation --- are exactly three times that of the input. The RF input is 14 mc with a deviation of ±1.25 kc; the output is 42 mc with a deviation of ±3.75 kc.

Second Doubler

Along with an increase of frequency and deviation for each multiplier stage, there is also a gradual increase of power at succesive stages. Thus, the tubes used in this and the following stages will be capable of delivering progressively higher amounts of power than the tubes of preceding stages. Other than this, the operation of the second doubler resembles that of the preceding multipliers. The input frequency to the second doubler is 42 mc with a deviation of ±3.75 kc. The output is therefore 84 mc, with a deviation of ±7.5 kc. Only one more multiplication is needed to reach the required output of 168 mc with a deviation of ±15 kc.



In the Preemphasized FM Transmission, Higher Audio Frequencies Cause Corresponding Greater Deviations.

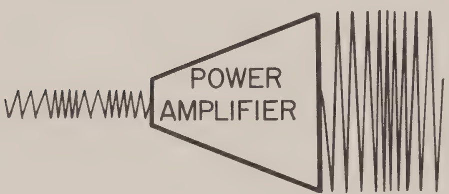
Doubler-Driver

The doubler-driver stage performs two important functions. First, as a frequency doubler the output signal will be the required channel frequency of 168 mc, and the deviation will be +15 kc. Second, the stage must supply sufficient energy to properly drive the final amplifier stage.

The doubler action is conventional enough and the characteristics of the preceding multipliers also apply to this stage. The original frequency of 7 mc, however, has come a long way by this time! It is true that this stage has only doubled the frequency of the preceding stage, but its plate circuit is now operating at the 24th harmonic of the oscillator frequency (7X24 = 168).

Any change in oscillator frequency, no matter how small, will

be multiplied 24 times in the final output. If the oscillator should change as much as 1 kc, the output will change 24 kc, enough to break contact with the receiver; a drift of only 100 cycles at the oscillator will cause a shift of 2.4 kc in the final output. These considerations, of course, properly concern the oscillator only, but they serve to illustrate the importance of a high degree of frequency stability on the part of the oscillator when the original oscillator frequency is multiplied.



The Power Amplifier Increases the Power (Amplitude) of the RF Wave. It does not Alter the Frequency or the Deviation.

The final amplifier requires considerable driving power, and this power must come from the plate circuit of the preceding stage --- in this case the double-driver. The tube selected as the driver must therefore be capable of handling larger amounts of power than the preceding stages; it is definitely in the "power amplifier" class. It must be remembered, too, that higher frequencies are involved in this stage than in earlier stages. Thus, in addition to its power requirements, the driver tube must be capable of providing satisfactory operation at higher frequencies.

Power Amplifier

The power output of any transmitter depends directly upon the final amplifier stage and its operation. The basic function of this stage is to build up the RF power to the required level---anywhere from 10 to 100 watts in mobile applications.

The power amplifier---unlike the previous stages---does not alter the frequency or deviation of the FM signal. Two factors are particularly important to the overall operation of the final stage; (1) in order to provide full or maximum power output the input drive must be high, and (2), the stage design must permit the efficient transfer of the available RF power to the antenna system.

The efficiency of the power amplifier depends largely upon the frequency of operation. Generally speaking, this efficiency varies inversly with the frequency. For example, while it is customary to regard 10 watts as average for smaller mobile transmitters and 60 or 100 watts for large ones, it must be remembered that a transmitter operating at a relatively low frequency can supply a greater amount of power output than a comparable unit operating at a higher frequency. Thus, the power available from mobile transmitters operating at 450 mc is considerably less than that at the lower frequencies.

The final stage of any transmitter is usually rich in harmonics

which must be minimized in the output. Harmonic signals cause objectionable interference on other channels. Harmonic suppression, since it takes place between the power amplifier and the antenna, must also be regarded as a function of the coupling and antenna circuits.

Antenna Circuit

What is called the antenna circuit of a transmitter includes more than just the antenna. All the units used to transfer the RF energy from the amplifier to the antenna help make up this circuit.

The most important requirement in the efficient transfer of RF energy from the final amplifier to the antenna is a proper impedance match between the separate units. Unless this is accomplished, too much energy is lost in the process and the power output is reduced. No matter how much RF power is available at the final amplifier, that power is of no practical use unless it is transferred to the antenna and radiated into space in the form of electromagnetic energy.

Summary

In this lesson we have discussed each stage in the phase modulated transmitter from the standpoint of its function and overall operation.

A comparison of the block diagrams of the phase modulated and direct FM transmitters showed that they differ from each other primarily in the method of modulation. Phase-modulated transmitters modulate the stage immediately following the oscillator---which is crystal controlled for maximum frequency stability.

The phase modulated wave has the characteristics of an FM wave, assuming that the FM transmitter includes preemphasis (which is usually the case). The FM receiver operates equally well for either wave.

In the lessons which follow, we shall discuss each stage of the transmitter in greater detail. Our discussion emphasized the extreme importance of the oscillator in the communications transmitter. This stage is discussed in detail in the next assignment.

IMPORTANT WORDS USED IN THIS LESSON

DEVIATION CONTROL: As applied to the phase-modulated transmitter, this refers to a system whereby the amplitude and waveform of the audio signal reaching the modulator is controlled in order to avoid excessive deviation of the carrier.

DOUBLER: A type of frequency multiplier in which the output frequency is the second harmonic of the input signal. In FM transmitters, the deviation as well as the carrier frequency is twice that of the input signal.

FREQUENCY MULTIPLIER: An amplifier stage in which the output is a harmonic of the input signal. Usually operated in class C, the frequency multiplier utilizes a circuit in the plate tuned to the desired harmonic frequency of the input.

IMPEDANCE MATCH: Where efficient power transfer is of prime importance, the impedance of the load must be made equal to the impedance of the source. This impedance match allows the transfer of the maximum amount of power from the source to the load.

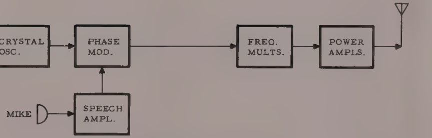
PHASE MODULATION: A type of modulation whereby the phase of the carrier is made to vary in accordance with the modulating signal. In effect, phase modulation is a form of FM, the difference being in the modulating characteristics of the signal.

PHASE MODULATOR: The stage within the PM transmitter in which the audio signal is made to phase-modulate the carrier.

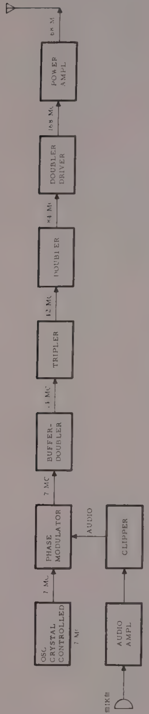
TRIPLER: A type of frequency multiplier in which the output frequency is the third harmonic of the input signal. In FM transmitters, the deviation as well as the carrier frequency is three times that of the input signal.

STUDENT NOTES

BASIC FREQUENCY MODULATED TRANSMITTER
FIGURE 1.



BASIC PHASE MODULATED TRANSMITTER
FIGURE 2.



BLOCK DIAGRAM
FM COMMUNICATIONS TRANSMITTER
FIGURE 3

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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-2
FM TRANSMITTERS

The Transmitter Oscillator

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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-2
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THE TRANSMITTER OSCILLATOR

LESSON TA-2

TABLE OF CONTENTS

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A "Handie Talkie" portable radiophone is the easiest way to quickly radio equip police patrol boats. The growing interest in water sports has necessitated corresponding increase in patrol duty on waterways and lakes.

THE TRANSMITTER OSCILLATOR

Lesson TA-2

Introduction

The FCC has effectively established a rather rigid standard for the stability of the transmitter. Although the concern of the FCC is with the operating frequency of the transmitter, the stability of the transmitter is in turn determined by its oscillator.

While the FCC requirements do not apply to the high-frequency oscillator in the receiver, the overall frequency stability of the receiver and the transmitter must be comparable in order to maintain reliable contact.

Because the requirements of the receiver oscillator and the transmitter oscillator are identical in many respects, and because both are crystal controlled, it is natural that these oscillators should be similar in design. There are differences, however, mainly in the operating frequency and power requirements. In this lesson we shall discuss these differences, as well as the specific oscillator circuits found in typical Motorola transmitters.

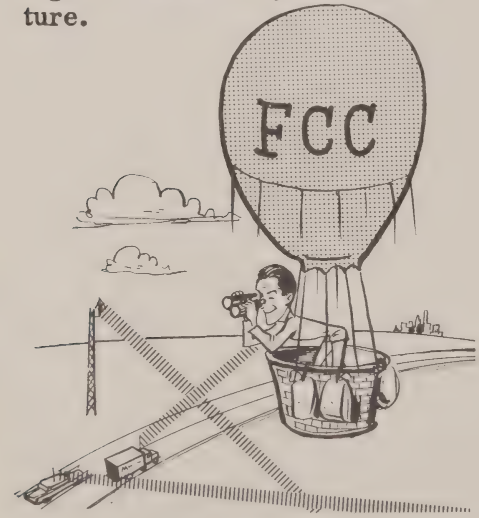
Frequency Stability

The frequency stability of an oscillator is determined by all the reactances in the circuit --- not just those of the frequency-determining tank. In low-frequency applications, most of the circuit values are stable and the small reactances do not noticeably affect the frequency. At higher frequencies, where the circuit reactances are of appreciable magnitude, circuit changes are bothersome to the point that the stability is far from satisfactory. This is one of the principal reasons for using a lower frequency oscillator, followed by a series of frequency multiplying stages.

Oscillator frequency is also influenced by changes either in the effective load resistance or in the plate resistance of the tube. The stability is improved by effectively isolating the plate circuit from the oscillator. One such method is the electron-coupled arrangement of figure 1. The frequency of an oscillator also depends upon the gain or transconductance of the tube. For this reason the "load"

must remain constant and the power supply must have good regulation.

The degree or amount of oscillator frequency change caused by the above factors depends a great deal upon the Q of the frequency determining tank. A high Q represents a large storage tank as far as maintaining a constant frequency is concerned, and this high Q counteracts circuit changes. Quartz crystals have by far the highest Q of any practical tuned circuit yet devised. The stability is further improved by maintaining a constant crystal temperature.



The FCC Regulates All Radio Transmissions Within its Jurisdiction.

Because the frequency of the crystal-controlled oscillator is considerably lower than the channel or operating frequency of the transmitter, it is necessary to use a series of harmonic amplifiers (frequency multipliers). One factor of frequency multiplication is its effect on any frequency variation of the oscillator. Where the carrier frequency is the 24th harmonic of the oscillator, as is often the case for transmitters operating in the high band, any change in oscillator frequency is multiplied 24 times at the channel frequency. While any change in frequency is increased in the process of multiplication, however, the frequency stability of the output signal is the same as that established by the oscillator---if the carrier frequency and the amount of any change are multiplied by the same amount, their ratio remains the same. The overall stability provided by this arrangement is still better than that attainable in other types of oscillators operating directly at the channel frequency.

In addition to the factors already mentioned in connection with frequency stability, we must not overlook the effect of the oscillator load upon the oscillator frequency. And when we speak of the load, we are immediately concerned with the power capabilities of the oscillator.

Power Requirements

Perhaps one of the most important circuit considerations in designing a stable oscillator is the amount of power it supplies to the circuits which follow it. Where the amount of power is kept to a minimum, and where the power consumption is constant, the greatest stability may be realized.

Power taken from the oscillator reflects a low resistance into the oscillator, and lowers the Q of the tuned circuits. This, in turn, means poor stability due to the lower Q. Or, if the power taken from the oscillator is used intermittently rather than at a constant rate, the stability is again sacrificed. Thus the circuits which are connected to the oscillator output, and which take power from that stage, must require a very minimum of driving power. The driving power required of the oscillator in modern Motorola transmitters is less than one watt. Even though this power is greater than that supplied by the receiver oscillator, the stage is still considered a low-powered device.

Where the oscillator supplies driving power both to the phase modulator and to the buffer-doubler following the modulator, it is essential that the buffer stage also requires but little driving power. (A heavy load at the buffer input produces non-linear modulation.)

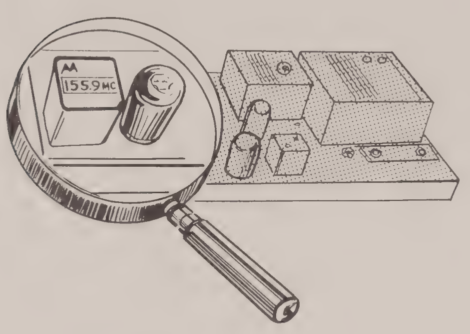
Load

From our discussion thus far, it may appear that the word "load" is being used rather freely in modern electronic practice, and this is surely the case. By basic definition (as applied to electricity and electronics), "load" means the power taken from a source of electric energy. Another way of saying the same thing is that the "load" is the power delivered by the source to some circuit component.

Load power may appear in the from of heat as in a resistor, in the form of a chemical reaction as in charging a battery, or it may be mechanical energy as in an electric motor. Unless some work is done, there is no load on the source; power must be dissipated or a transfer of energy must take place. A heavy load means that a lot of power is taken from the source; a light load means that little power is used.

"Load" is also employed as a verb. When a circuit is connected to a source of power and that circuit absorbs energy, we say that the circuit "loads" the source. When the antenna of a transmitter is coupled to the power amplifier and RF power is taken from the amplifier---and transferred to the antenna---we say that we "load" the antenna.

In modern electronics, the word has also by common usage, been applied to the unit which we connect to a source, or across which we develop signal voltages. Thus the speaker is the load on an amplifier, the antenna is the load on a transmitter, etc. A resistor placed in the plate circuit of a tube and across which the desired signal voltage is developed, is commonly called the "plate-load resistor."



The Operating Frequency and the Frequency Stability of the Transmitter are Determined by the Oscillator.

The Oscillator Load

Any RF power which is dissipated within the oscillator stage, or supplied by the oscillator to the following stage, is the load on the oscillator. Common examples are the power within the plate circuit of the oscillator, and the power supplied to the grid circuit of the following stage. The RF power used internally in the tube is also an RF loss. In oscillator design, all these power requirements must be recognized and provided for.

The tube selected for the oscillator stage must readily handle the required power and still have some power in reserve. In figure 1, the 6AK6 tube is capable of supplying several watts of RF power when operated in class C. The circuit requirements, however, will normally be less than one watt. This means that the tube is just "loafing along." The tube also does not operate as hot as if maximum power were used, and this results in greater stability and longer tube life.

Another consideration is the proportion of RF and audio voltages supplied to the modulator. The amount of deviation resulting from a specific amount of audio signal depends to some extent upon the relative values of the audio and RF voltages. If the oscillator input to the modulator should vary for some reason, the amount of deviation will also change. This is of course undesirable. Operating the oscillator below its maximum power capabilities assures a more constant output, resulting in improved frequency stability and modulation linearity.

In figure 1, as in many Motorola transmitter oscillators, the plate tank has been omitted. Instead, we find a plate resistor. A resistor maintains a nearly constant load---much better than a tuned circuit---and this improves the stability. In addition, the electron-coupled arrangement between the oscillator section and the plate circuit effectively isolates the output from the oscillator. This further reduces any effect of the plate load upon the oscillator and improves the stability of the circuit.

The RF voltage from the oscillator plate circuit is applied both to the phase modulator grid and to the grid of the buffer-doubler. The power consumed in these two grid circuits thus comes from the oscillator (and modulator) stage and this power dissipation is held to a very minimum.

Operating Frequency

As we know, the operating frequency of the oscillator in present-day transmitters is considerably below the channel frequency. There are two basic reasons for this practice. First, a highly stable oscillator operating at the channel frequency is not practicable---greater stability is realized by a lower-frequency oscillator followed by frequency multipliers. Second, full deviation cannot be realized at the phase modulator with any degree of linearity. Thus it is necessary to start with a small amount of deviation at the modulator and achieve the required deviation at the output by means of frequency multiplication.

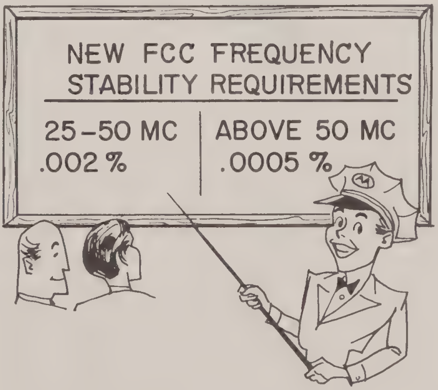
The amount of frequency multiplication required for a given transmitter depends upon (1) the final required deviation at the output and (2) the maximum deviation that can be produced at the modulator (without too much distortion). For example, let us suppose that the required deviation at the output is 15 kc, and that the modulator may produce a maximum deviation of 950 cps. The amount of frequency multiplication will then be 16 times, (15 ÷ .950). This is the approximate amount of frequency multiplication to be used in the transmitter.

By dividing the frequency multiplication into the operating range of the transmitter, the frequency range of the oscillator can be determined. For a transmitter with an operating range of 144-174 mc, for example, we first divide 144 by the frequency multiplication factor (16), and then divide 174 by this same factor, 16. The oscillator frequency range will be found to be approximately 9-11 mc. Again, for the same system operating on the low band (25-54 mc), the oscillator frequency range is found by this method to be approximately 2-3.5 mc.

Thus we find that oscillators in low-band transmitters have a comparatively low frequency, whereas oscillators for high-frequency transmitters may have a considerably higher frequency. With this thought in mind, we are ready to start our study of the various types of oscillators found in Motorola transmitters.

High-Band Oscillator

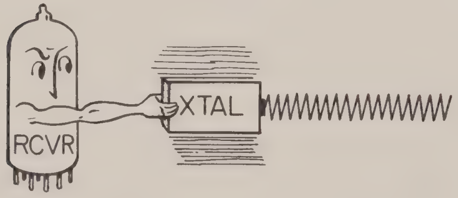
It is common, in high-band transmitters, to encounter output frequencies which are the 24th harmonic of the oscillator frequency. This means that the



The FCC Recently Established Rigid Frequency Stability Requirements for Two-Way Radio Systems.

oscillator will be operating in the 6-7 mc range. For example, if we use the frequency values of the transmitter block-diagram shown in the preceding lesson (where the output frequency is 168 mc), a multiplication factor of 24 results in an oscillator frequency of 7 mc.

For a deviation of 15 kc at the output, a required deviation of only 625 cps is needed at the phase modulator. With this small deviation at the modulator, the linearity will be very good.



The Receiver Oscillator Operates at a Comparatively High Frequency but Delivers Very Little RF Power.

The oscillator circuit of figure 1 is similar to the high-frequency oscillator studied in the receiver section of this training. Several differences are noted, however. While the crystal operates as a series resonant circuit, the oscillation is at the fundamental frequency rather than at the third harmonic mode.

Many of the component values are different in order to compensate for the lower operating frequency and the higher output power. In the receiver oscillator, the plate circuit is tuned to the fifth harmonic of the oscillator and provides the required signal into the mixer. The transmitter oscillator plate load is a resistor, with capacitive coupling to the following stage.

A meter position in the grid circuit allows for adjusting the tuned grid circuit for maximum oscillator activity. This adjustment has a small effect on the oscillator frequency, but the warping capacitor in series with the crystal allows the oscillator to be placed at the exact frequency required.

Low-Frequency Oscillator

Figure 2 shows a Colpitts type oscillator found in many Motorola low-band transmitters. At lower frequencies, the overall stability of this circuit may be better than that of figure 1 operating in the same frequency range.

Because the operating frequency of the transmitter is relatively low, between 25 and 54 mc, the oscillator frequency will be correspondingly low, between 2 and 4 mc. This permits a high order of frequency multiplication to be obtained (12 times), with only a small deviation required at the phase modulator. If the oscillator were to operate at a higher frequency---closer to the channel frequency---there would be less frequency multiplication, and consequently a large deviation would be required at the modulator.

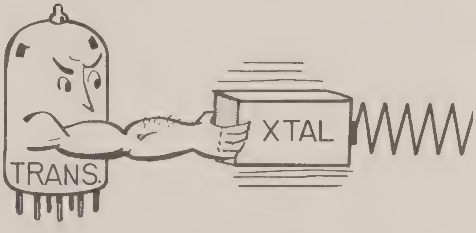
The crystal operates as a parallel resonant tank and it is the frequency-determining factor for the oscillator. Feedback is secured across the capacitor in parallel with the cathode coil, and the amount of feedback is determined by the ratio of the two series capacitors. The variable warping capacitor, paralled to the crystal, provides for minor frequency adjustments. Circuit operation is essentially the same as that of the second (or low-frequency) oscillator of the receiver.

In the oscillator circuit of figure 2, there is no need for a metering position. There is no tuned circuit which requires adjustment, and the oscillator output is maximum at all times. We can change the operating frequency of the transmitter by substituting a crystal of another frequency. The rest of the transmitter stages are then aligned in the normal manner for maximum output and the transmitter is placed on the exact channel frequency by means of the warping capacitor.

The High-Frequency Oscillator

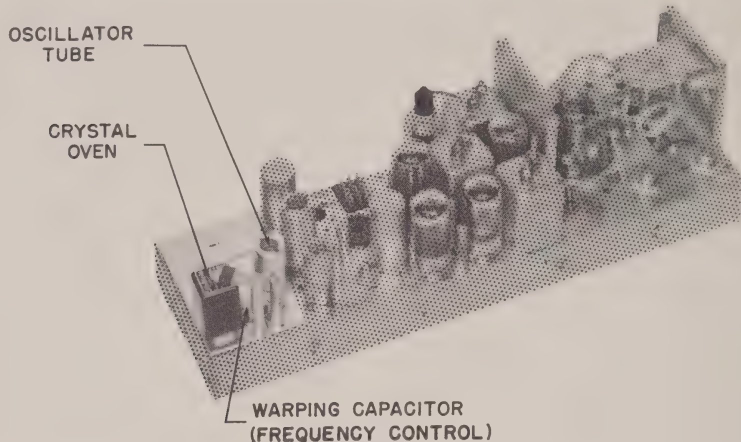
Figure 3 shows the type of oscillator circuit used in many Motorola 450-mc transmitters. Its operating frequency is between 18 and 20 mc, and this relatively high frequency is necessitated by the 450-mc output of the transmitter.

If an oscillator in the 6 or 8 mc range were used, the frequency multiplication factor would be so high as to be impracticable, for too much multiplication increases both the spurious and harmonic output of the transmitter. Thus, the oscillator frequency must be higher in order to limit the multiplication to a practical value, but at the same time the frequency must not be so high that the stability is unduly sacrificed. An 18-20 mc oscillator satisfies both these requirements--the multiplication is 24 times.



The Operating Frequency of the Transmitter Oscillator is Lower than that of the Receiver, But There is Considerably More Power Available.

The oscillator circuit of figure 3, unlike those of figures 1 and 2, uses a twin triode. The first triode is the oscillator half of the tube; the second triode section is a feedback amplifier and phase shifter. Voltage from the cathode of the second section is fed back to the cathode of the first triode, and this feedback voltage has the phase and amplitude required for oscillation.



This Photo of a Typical Motorola Transmitter shows the Location of the Oscillator Components.

The grid of the oscillator is at ground potential, as far as the oscillation frequency is concerned. In fact, the circuit will oscilate only when this grid is at ground RF potential. The crystal acts as a series resonant circuit---at the resonant frequency it offers little or no impedance to the signal, placing the grid at ground potential. At all other frequencies the crystal offers a high impedance, and the grid is no longer grounded. The circuit cannot oscillate.

The crystal is cut to oscillate on its third harmonic, and the plate tank is tuned to this same frequency. The frequency of oscillation can be altered to some extent by changing the phase of the feedback voltage. This is accomplished by adjusting the oscillator plate tank. Changing the frequency of the plate tank varies the phase of the signal applied to the grid of the second triode, and this, in turn, changes the phase of the voltage fed back to the oscillator section. This provides a small change in the operating frequency, allowing the oscillator to be placed on the exact channel frequency.

A meter in the amplifier grid circuit measures the amount of RF signal (by measuring the grid bias) and thus indicates the strength of the oscillation. Normally it is not necessary to use this reading in aligning the transmitter, but it serves as a helpful device in trouble-shooting the transmitter, for it indicates the general condition of the oscillator (crystal activity).

This meter reading is also helpful when it is necessary to change the transmitter frequency. When a crystal cut for a different frequency is installed, the circuits will be off-resonance, the oscilator output will be low, and there may not be sufficient drive at the multipliers to provide a reading. By adjusting the oscillator plate tank for a maximum reading, the

oscillator will be brought near resonance and the output voltage will be nearly normal. The rest of the transmitter circuits may now be adjusted in the normal manner. Then, after the entire transmitter has been tuned, the final frequency setting may be made. (If necessary, the other stages should be retuned for optimum operation.)

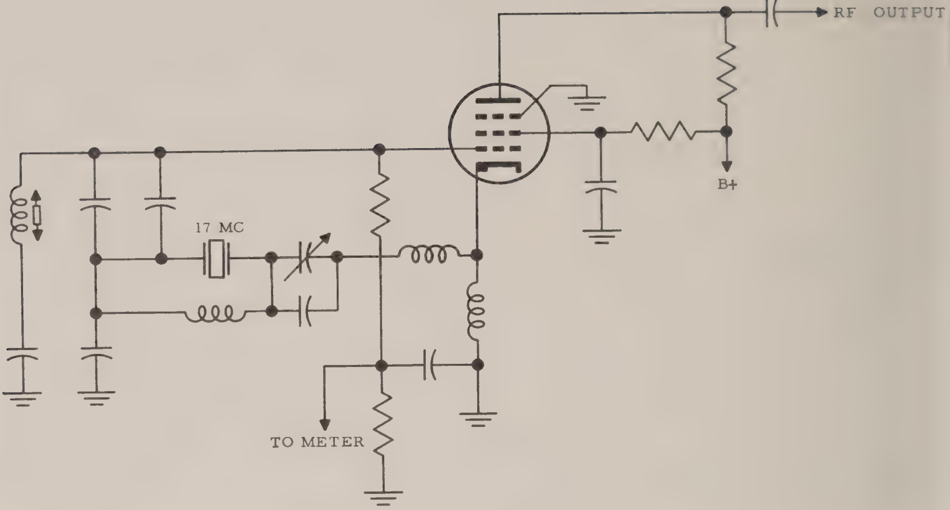
Two-Frequency Operation

Sometimes it is desirable to transmit (and receive) on either of two frequencies within the same band. For reasons of economy and space, it is essential for both frequencies to be provided by one transmitter. An example of this is afforded by a local police department, where communication is required both with the local cars and with the county and state police.

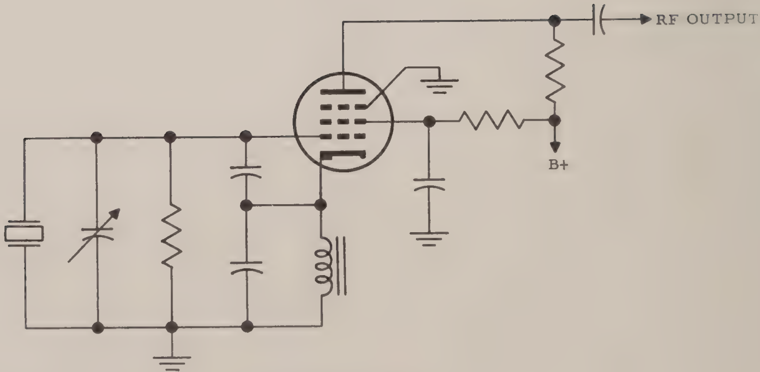
The system shown in figure 4, devised for this purpose, employs two separate oscillators. Only one of these oscillators is in operation at any one time. This is accomplished by means of a switch which grounds the cathode of the desired oscillator.

The oscillators are completely independent of each other, even though the plate and screens are connected together. Selection of either oscillator is made by means of a swtich on the operator's control head. Only the oscillator which is selected can operate, for the cathode of the other tube is open. Bypass capacitors at the lower ends of the cathode coils maintain these points at RF ground potential. The wires leading from the oscillators to the frequency-selecting switch are at ground potential for both DC and RF. Because the cathode of only one of the oscillators is grounded by means of the switch, only one tube can conduct at a time, and the circuit currents are the same as if it were a single-frequency transmitter.

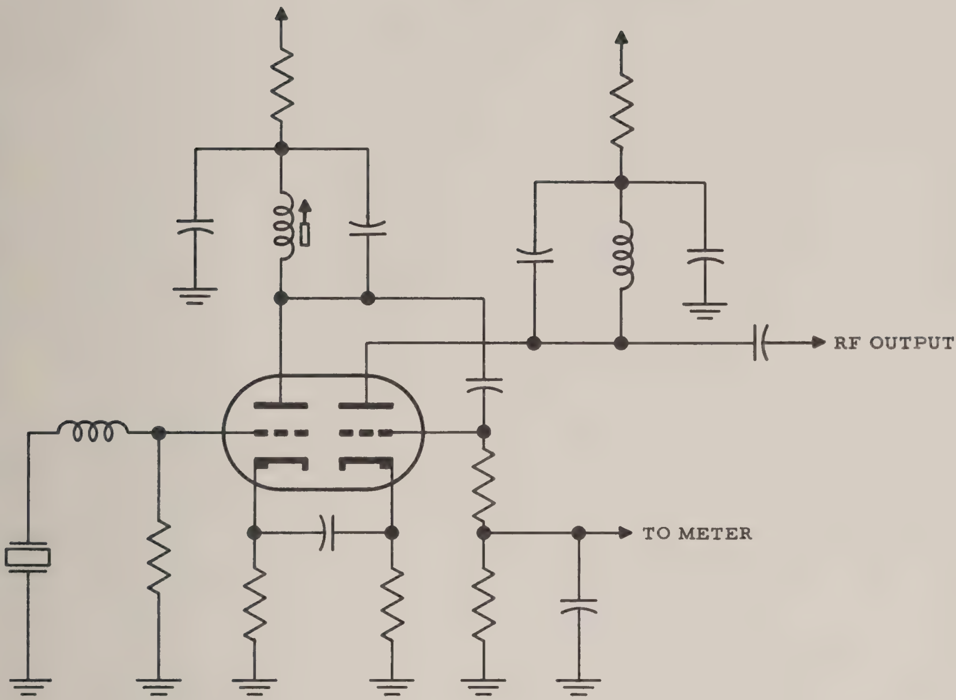
As long as the two frequencies are reasonably close together, the tuned circuits of the transmitter produce a normal output at either frequency. Frequencies as far apart as 400 kc (for high-band transmitters) are practical without degrading the operation of the transmitter on either frequency. Where the frequencies are this far apart, however, the transmitter should be tuned to the mid-frequency for best results.



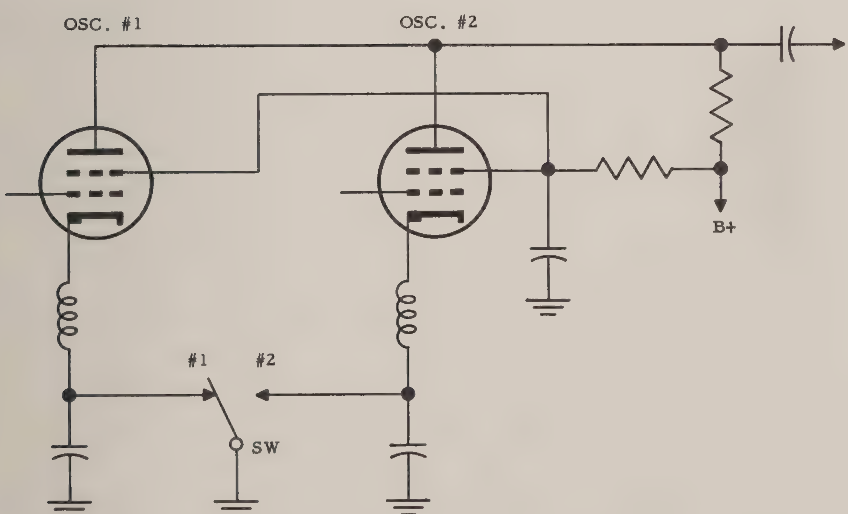
TRANSMITTER OSCILLATOR
FIGURE 1.



2-4 MC OSCILLATOR
FIGURE 2



16-20 MC OSCILLATOR
FIGURE 3



TWO FREQUENCY OPERATION
FIGURE 4.

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LESSON TA-3
FM TRANSMITTERS

The Phase Modulator

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-3
FM TRANSMITTERS

The Phase Modulator

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
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APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

THE PHASE MODULATOR

LESSON TA-3

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Metropolitan area public works departments, involved in many types of operations, utilize extensive two-way radio communications systems to control all facets of their work.

THE PHASE MODULATOR

Lesson TA-3

Introduction

For the requirements of present-day mobile two-way FM transmitters,the phase modulator circuit is one of the most practical methods of securing frequency modulation.

In this lesson we shall be concerned with the operation of the phase modulator. We shall consider the effect of the audio modulating voltage in producing a phase-modulated wave and see, in turn, how this constitutes frequency modulation. We shall also learn that the amount of this frequency deviation is determined both by the audio amplitude and the audio frequency---not by the audio amplitude alone, as in a direct FM system.

If we are to analyze the operation of the phase modulator and understand the nature of phase modulation, it is necessary for us to know the meaning of the word "phase."

Phase

Physicists define "phase" as that point or stage in the period to which a rotation, oscillation, or variation has advanced, from a starting position or assumed instant of starting. In electronics we use phase in a similar manner, applying it to alternating current and voltage relationships. Let's see how we portray this graphically.

In figure 1A, time is plotted horizontally, from left to right. Because the sinewave is derived from the rotating vector and the circular or angular motion of the rotating vector is measured in degrees, we mark the time periods of these sinewaves in degrees. We therefore refer to the 45°, 90° and other points along the horizontal axis as the 45° phase, the 90° phase, etc. In this sense, "phase" refers to the actual angular rotation---the extent of rotation---that has taken place.

Here is how we use the word phase with relation to the sinewave of figure 1A. We say, at its 90° phase the waveform has reached its maximum positive amplitude. At its 180° phase the instantaneous amplitude of the waveform is zero. In each of these examples "phase" measures the time period of the waveform from its starting point at 0°.

In addition to this fundamental concept, we also use the word

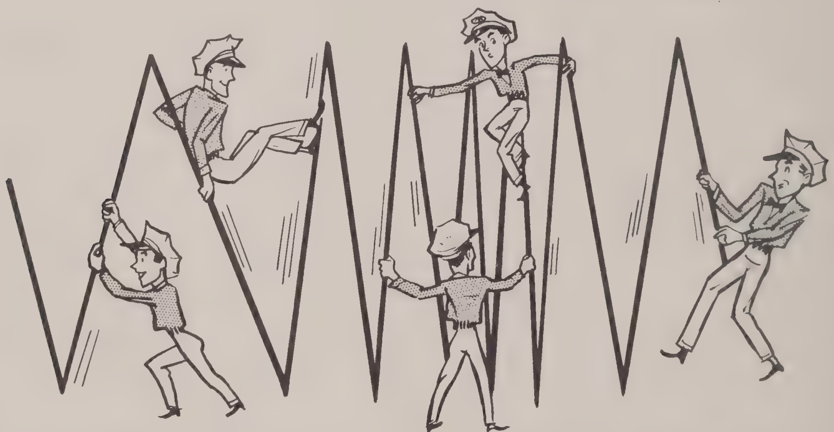
phase when making a time comparison between two alternating voltages, two alternating currents, or between an alternating voltage and current.

In figure 1B, for example, we have two sinewaves with all their corresponding instantaneous values occurring at the same time. That is, when sinewave A is at its zero value, sinewave B also is at zero; when A is maximum positive or negative, B is also maximum positive or negative. These waveforms are "in phase."

is leading sinewave A by 45°. Or, we may say that A lags B by 45°.

Vectors Show Phase Displacement

Vectors may also be used to show phase relationships. In figure 1E, vectors A and B are both shown at their 0° phase. As these vectors rotate at the same speed, they will reach all of their various positions simultaneously. These vectors are then "in phase" and have the same relationship as the sinewaves of figure 1B.



FM may be Produced by Advancing and Retarding the Phase of an RF Wave.

In figure 1C, the waveforms are not in phase. Instead, sinewave A passes through its various values just 90° ahead of sinewave B. This is termed a 90° "phase displacement" between the two waveforms, with A leading B by 90°. You can also see that B is lagging A by 90°.

A further example of two sinewaves being out of phase is shown in figure 1D. Here sinewave B

In figure 1F, vector A is again shown at its 0° position, but vector B is shown lagging A by 90°. Again assuming A and B to have the same speed of rotation, when A has moved to the 90° (vertical) position, B will still lag by 90° and will be at the 0° position. At any instant of time A will always lead B by 90°. Therefore, the phase difference between these two vectors is 90°, with A leading. This shows the same phase relationship as figure 1C.

In figure 1G vector B has been drawn to lead A by 45^o. This corresponds to figure 1D. It is interesting to note that even though these vectors may not be in phase, they have the same frequency. That is, as long as the vectors (or the sinewaves) maintain a constant phase relationship, they have the same frequency. The reason for this is that in a given amount of time they will complete the same number of cycles.

In figure 2A, vector A represents the 7-mc oscillator voltage used in the Motorola high-band transmitter. Because the oscillator has a constant frequency and phase, vector A is used as the reference for this diagram and is drawn to the right. Vector B represents another (unidentified, for the present) voltage within the phase modulator.

Assume that the phase relationship between these two vectors (voltages) remains constant, so that the vectors are 45^o apart at all times. The frequency of both voltages must then be constant at 7 mc. Figure 2B shows the same relationship in sinewave representation. The phase displacement between the waveforms is 45^o, with B lagging A.

Let us consider next the condition illustrated in figure 3A. Assume something happens instantaneously within the circuit to move B closer to A. In position 2 vector B now lags A by 35^o. As long as vector B maintains this new phase relationship to vector A, its frequency will still be 7 mc the same as before.

Thus, vector B may again change in phase so that it is lagging A by 55^o (position 3), but if this phase relationship remains constant, its frequency will still be 7 mc. As long as the two vectors rotate at the same rate (maintain a constant phase relationship) the frequencies of the AC voltages represented must be the same.

In the discussion above we assumed that any phase change was sudden, and that immediately thereafter the two vectors retained a constant phase relationship. As we will see in the phase modulator, however, the audio modulating signal causes a change of phase between the RF voltages which is not instantaneous. Figure 3B illustrates this changing phase relationship between the two vectors.

When the modulating audio voltage (shown at the lower right of the figure) is at its zero amplitude, vector B will be in position 1. On the positive audio voltage peak vector B advances in phase to position 2. On the negative peak the vector retards in phase to position 3. Furthermore, the variation of the signal between peak values occurs over a finite period rather than instantaneously. This produces a more gradual change in the phase of the RF voltage.

The question immediately arises, "What happens when the phase is changing?" Let's consider the frequency of vector B when it advances in phase, as from position 1 to position 2. During the time it takes vector A to make one complete cycle or revolution, vector B must complete one full revolution and a little more. This is because B has now moved closer to A in phase. To accomplish this, B must have moved through its rotation faster with the resultant increase in its frequency.

Thus, when the phase of a vector is "advanced" with respect to a constantly rotating vector, the frequency of the advancing vector is increased. Furthermore, the amount of frequency change (frequency deviation) depends upon the rate of phase advancement of B. When the phase increases slowly, the amount of deviation is small. If the phase advancement is at a high rate, the deviation must be high.

When the phase of B is retarded, as from position 2 of figure 3B to position 3, the frequency of B must be lower than that of A. Unless the frequency of B is lower than that of A (rotates at a slower rate) there can be no retarding of its phase. This means a negative deviation, or deviation below the center frequency of 7 mc. The amount of frequency deviation is again determined by the rate of change in phase.[1]

The phase change taking place for RF vector B, as we shall soon see, is the result of an audio voltage applied to the modulator stage. Thus, the amount of frequency deviation is determined by the rate of phase change caused by the audio voltage. Should the audio voltage cause a small rate of phase change during some portions of its applied voltage, the frequency deviation of the RF vector during this time will be comparatively small. Or if the audio waveform is such that at other times the phase of the vector changes rapidly, the amount of deviation will be comparatively higher. Our next problem, then, is to determine the rate of change within the audio modulating signal. For convenience, let us assume a sinewave audio voltage.

Rate of Change

Figure 4A illustrates the variation in the rate of change of the amplitude of a sinewave. The degree of rotation (time) is plotted horizontally, and amplitude is plotted vertically. The amplitude of the wave at its various phases is given in the accompanying chart.

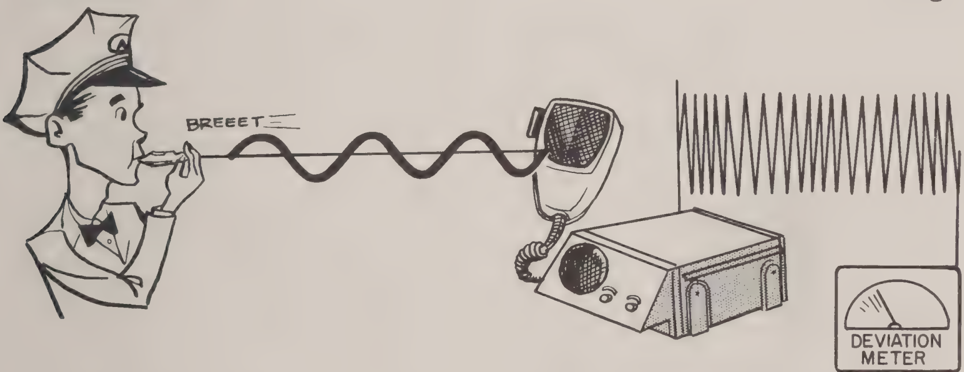
The time period between the 0° and 15° phases is the same as the time period between the 75° and 90° phases. Between 0° and 15°, however, the amplitude increases from zero to 26% of maximum, while between 75° and 90° the amplitude increases from 97% to 100% of maximum, a total change

1. See TM 11-668 FM Transmitters and Receivers, pages 5-7; also FM Transmission and Reception, by Rider and Uslan, pages 12-13.

of but 3%. This means that the rate of amplitude change in the vicinity of the 0° phase is much greater than the rate of change at the 90° phase. In fact, at the peaks of the sinewave (90° and 270°) the rate of change is momentarily zero. At the points of zero amplitude (0° and 180°) the rate of change is maximum. The sinewave audio voltage, then, has a high rate of change at some portions, a low rate at others. Because the audio voltage causes variations in the phase of the RF voltage in the phase modulator, there will be intervals with little or no phase variation, but there will also be intervals with considerable variation.

The arrows in curve A of figure 4B show the various rates of change. Where the arrow is horizontal, as at the positive and negative peaks, the rate of change is momentarily zero. (Even though the amplitude is maximum, the voltage is neither increasing nor decreasing.) Thus, at these instantaneous times---at the positive and negative peaks of the sinewave ---the rate of amplitude change must be zero.

Curve B shows the rate of change of curve A. Thus, B must have its maximum values during those times when A is momentarily zero, and vice versa. Because curve B shows the rate of change



In an FM System, a Weak (Low Amplitude) Audio Causes Little Deviation Within the FM Wave.

Look at figure 4B. Because the vertical displacement of the wave shows amplitude, and time is plotted horizontally, the vertical slant or slope of the wave at any point is the rate of change. The exact rate of change of the sinewave can thus be analyzed from the "slope" of the wave.

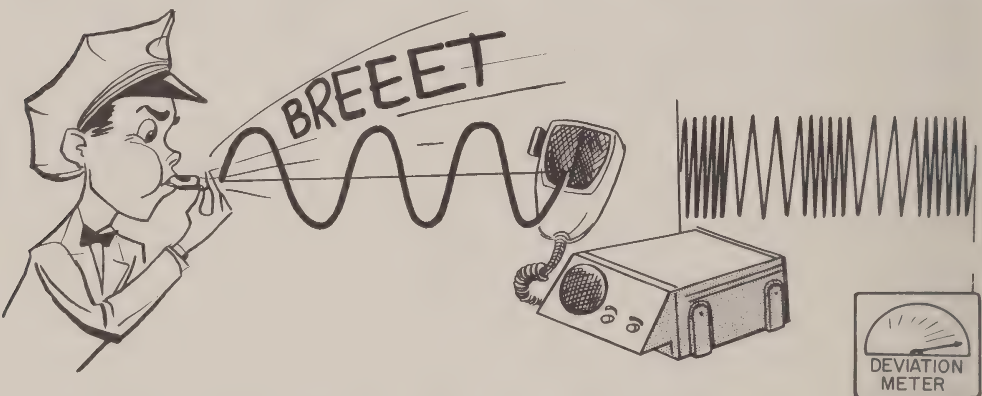
of the sinewave, it also indicates the frequency deviation produced when waveform A is applied to a phase modulator.

Analyzing this further, when the audio voltage is at its peak value, the rate of change is zero and there is no deviation of the RF

signal ---- the RF is at center frequency (7 mc.). At the instant when the audio voltage has zero amplitude, the rate of change is maximum and there is maximum deviation (either positive or negative according to whether the audio is going in a positive or negative direction).

that of A, this greater amplitude change must take place in the same amount of time. The rate of change of B must therefore be twice that of A. The rate of change of a sinewave varies directly with the amplitude of the wave.

This is desirable, of course, for



In an FM System, a Strong (High Amplitude) Audio Causes Considerable Deviation Within the FM Wave.

if a person talks louder into the microphone the audio voltage should be greater to increase the amount of deviation. At the receiver, this greater deviation produces a greater (stronger) discriminator output and a louder reproduction at the speaker. This effect takes place as long as the audio signal at the clipper stage does not exceed the clip level. When this happens, the deviation no longer increases with the increased voice level.

Both the amplitude and the frequency of the audio signal affect its slope or rate of amplitude change. An increase in either the amplitude or frequency increases the slope and hence causes a greater deviation in the phase modulator. These effects can be seen in figures 5 and 6.

In figure 5 the two audio waveforms have the same frequency, but the amplitude of B is twice that of A. Since the frequency of the two waves is the same, each complete cycle requires the same amount of time. Thus, both waves change from one peak to the other in the same length of time. Although the amplitude of B is twice

The effect of the audio frequency on rate of change is seen in figure 6. Here the amplitude of both waves is the same, but the frequency of B is twice that of A.

(Each cycle of B occurs in one-half the time it takes for one cycle of A.) If B changes from one peak to another in half the time, and the peaks of B are as great as those of A, the rate of change of B must be twice that of A. This means an audio signal having twice the frequency of another will cause twice the amount of deviation in a phase modulator. The rate of change will vary directly with the frequency.

This effect is desirable in one respect, for it adds a natural pre-emphasis to the modulation --- a pre-emphasis of 6 db per octave. (Pre-emphasis is needed to improve the signal-to-noise ratio of the upper voice frequencies, and is used almost universally in FM transmissions). The amount of pre-emphasis is 6 db per octave for the following reason. If the audio frequency is doubled, the amount of deviation is also doubled, and has the same effect as if the audio amplitude were doubled. Because two-to-one voltage ratio is 6 db, the increase caused by doubling the frequency (equal to one octave) is also 6 db.[2]

From the above we see that the amount of frequency deviation resulting in a phase modulation system depends upon both the frequency and the amplitude of the audio modulating voltage. Now that we know the factors involved in phase modulation, let's see how they apply to a practical circuit.

Phase Modulator Circuit

In the phase modulator of figure 7, two RF voltages combine to produce a phase modulated signal in the output. This signal is applied to the buffer grid-circuit. The operation is as follows. The constant 7-mc signal from the oscillator is present at the modulator output, coupled through capacitors C1 and C3. This voltage is present at the output (the buffer grid) even though the modulator tube may be inoperative. In fact, the modulator tube can be removed from its socket without greatly affecting this voltage.

Another voltage in the output is that applied to the grid of the modulator from the oscillator, amplified through the tube, and coupled to the buffer grid through C3. The voltage applied directly from the oscillator has a constant amplitude and frequency and does not depend upon the operation of the modulator. The voltage from the modulator tube depends upon tube amplification. (We shall later see how the amplification of the stage will be controlled by an audio signal which is also applied to the modulator grid.)

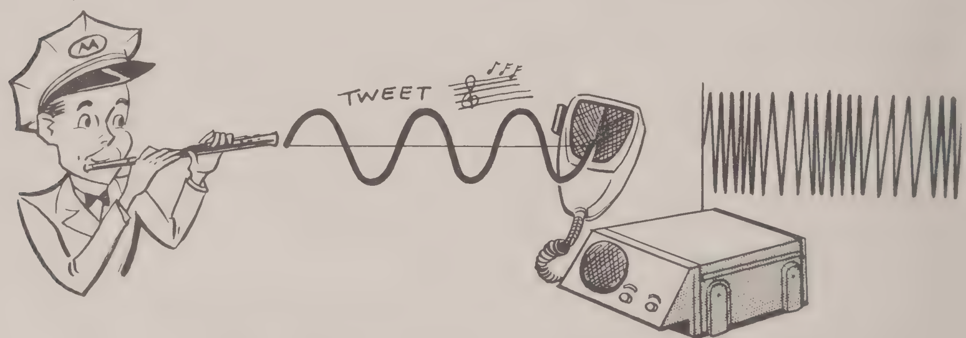
The two RF voltages in the modulator output are represented vectorially in figure 8A. The voltage applied directly from the oscillator (E_{osc}) is constant in frequency, phase and amplitude; it is there-

2. See TM 11-668 FM Transmitters and Receivers, pages 8-10.

fore used as the reference voltage and drawn to the right. The RF voltage due to tube amplification (E_{ampl}) is normally almost 180° out of phase with the voltage applied to the modulator grid. The circuit values have been selected so that the phase is somewhat less than 180°, as shown.

alternately more and less negative to the cathode, causing the RF voltage in the plate circuit to change in amplitude at the audio rate. Figure 8B shows how this takes place.

The $E_{ampl.}$ vector varies alternately from its normal length



High-Frequency Audio Signals Cause Many Deviations per Second within the FM Wave.

With these two RF voltages present, the effective voltage (E_{total}) is the vector sum of the two. Unless an audio is applied to the modulator, the vectors continue to rotate in orderly fashion and the output is constant at the 7-mc oscillator frequency.

Now, let us see what happens when we apply the modulation. When an audio voltage is applied to the modulator grid, only the RF voltage which is due to the amplification of the tube is affected. The voltage applied directly from the oscillator remains constant; neither its frequency, its phase nor its amplitude changes. Voltage $E_{ampl.}$ (due to tube amplification) varies in amplitude at the audio rate, for the audio makes the grid

(A), to B on the positive audio peaks, and to C on the negative peaks of the audio voltage. With $E_{osc.}$ remaining constant and $E_{ampl.}$ changing its length, the resulting total voltage varies between positions A', B', and C'. (These resultants are found by the now familiar parallelogram method.

While there may be a small amplitude change of the output voltage, the most important effect is its phase advancement and retardation. Because the phase change of the resultant output voltage is caused by an audio voltage, those phase variations in the RF must follow the same audio waveform, as shown. Furthermore, the rate of phase change will be de-

termined by the rate of change of the applied audio signal, and this, as we already know, is determined by both the amplitude and the frequency of the audio.

The phase modulated vector of figure 8B is essentially the same as that of figure 3B. The audio voltage causes the vector to advance and retard at the audio rate and the rate of change in phase, as we have seen, depends upon both the audio amplitude and audio frequency. Either of these --- a greater audio amplitude or a higher audio frequency --- increases the rate of phase change in the RF output voltage and produces a greater frequency deviation. Because this changing phase represents frequency modulation, the phase modulator is a means of producing FM; as we will see, the output waveform has the same characteristics of a preemphasized FM wave.

The exact amount of frequency deviation produced at the phase modulator may be determined by the formula,

$$\Delta F = f \times \Delta\phi$$

where,

ΔF is the frequency deviation produced, in cps,

f is the audio frequency, and $\Delta\phi$ is the maximum phase angle, in radians, through which the carrier is shifted.

(The "radian" is a measure of angular rotation and is used extensively in vector representation. One radian is the amount of rotation by the vector which produces an arc having the same length as the radius. This is always equal to 57.3°. Also, in one complete circle there are always 6.28 radians. The value 6.28 is numerically equal to 2π and explains the presence of this term in almost all AC formulas.)

EXAMPLE:

An audio signal of 1000 cps causes a phase shift of 2.5 radians. What is the resulting deviation?

Substituting in the formula,

deviation = 1000 x 2.5 = 2500 cycles, or 2.5 kc.

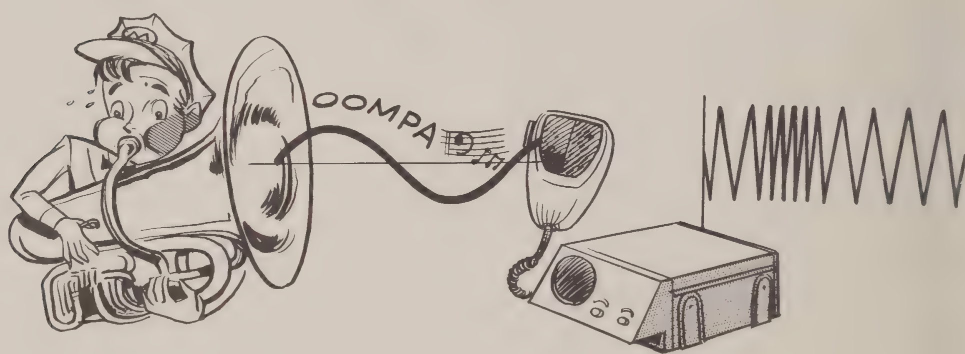
(Note, from the above formula, that any increase in audio frequency increases the amount of frequency deviation.)[3]

Preemphasis and The Phase Modulator

We have already seen that one audio voltage having twice the frequency of another audio voltage also has twice the rate of amplitude change, resulting in twice as much deviation in the phase modulator. Moreover, doubling the audio frequency has the same effect on the amount of deviation as has the doubling of the audio amplitude. Thus, the phase modulator has a preemphasized output---the preemphasis being 6 db per octave.

3. See TM 11-668 FM Transmitters and Receivers, pages 50-54; also FM Transmission and Reception, by Rider and Uslan, pages 176-182.

While this natural preemphasis of the phase modulator seems to be advantageous, there are certain factors which may make it undesirable. Noise voltages, for instance, regardless of their origin, contain a large amount of high frequency energy. Should these voltages reach the phase modulator, the preemphasis will cause excessive deviation.



Low-Frequency Audio Signals Cause Only a Few Deviations of the FM Wave During Each Second.

The nature of vocal sounds presents an additional problem. Most audio waveforms produced by the speaking voice contain sharp and irregular pulses rather than sine-wave patterns, and this high harmonic content overdeviates the transmitter. It is thus essential to include some means of limiting the amount of deviation by controlling the waveform of the signal applied to the phase modulator.

These high frequency components not only cause overdeviation and possible interference on other channels; they also expend too much of the energy at the transmitter --- energy that should normally be used for voice modulation. This causes a proportional degradation of the messages we wish to hear.

In the lesson on the audio section of the transmitter, which follows this one, we shall see how the waveshape of the audio signal is controlled so that the transmitter cannot be overdeviated by high-frequency components, nor by excessively high audio voltages originating at the microphone.

Motorola Phase Modulator

The modulator circuits used in older equipments were seriously handicapped by the limited amount of frequency deviation that could be produced without causing distortion. Beyond a certain limited amount of frequency shift, any additional deviation was no longer linear with respect to the amount of signal amplitude. With the amount of deviation at the modulator limited by necessity to the

maximum swing without distortion, the oscillator had to operate on a low frequency with a great number of frequency multipliers following the modulator. This was a distinct disadvantage.

As crystal oscillators at higher frequencies became more practical, the need arose for a modulator capable of greater deviation without distortion. The Motorola phase modulator circuit of figure 7 offers such an arrangement. Theoretically, it has modulation linearity up to 180° of total phase swing, and this means that fewer multiplication stages are required ---greater deviation is practical.

Although the theoretical limit of the Motorola modulator is $\pm 90^{\circ}$, a maximum linearity of about $\pm 70^{\circ}$ is all that should be realized in a practical circuit, due to tube changes and other effects. The phase of the output voltage varies 180° as the modulator tube changes in transconductance from zero to infinity, but this cannot be realized, in practice, in the mobile two-way transmitter.

Although this concludes our analysis of the operation of the phase modulator as used in the two-way FM transmitter, before we can fully appreciate the resulting frequency modulated wave it is necessary to study the sidebands which have been produced.

Sidebands and Bandwidth

In an earlier discussion of bandwidth we assumed that the frequency deviation each side of the carrier constituted the energy distribution of the FM wave. Actually this is not the entire picture, for the sidebands of the FM signal must also be taken into consideration. Before discussing FM sidebands, however, let us look at sidebands in general --- both AM and FM --- and then compare the two systems.

In any modulation method, combining the audio signal with the RF carrier produces energy at different frequencies and these new frequencies are always separated from the RF carrier by an amount equal to the audio frequency. For instance, if the audio frequency is 5 kc the sideband frequencies are 5 kc above and 5 kc below the carrier frequency. This is known as one pair of sidebands. Similarly, a 10-kc modulating signal produces sidebands 10 kc above and below the carrier frequency.

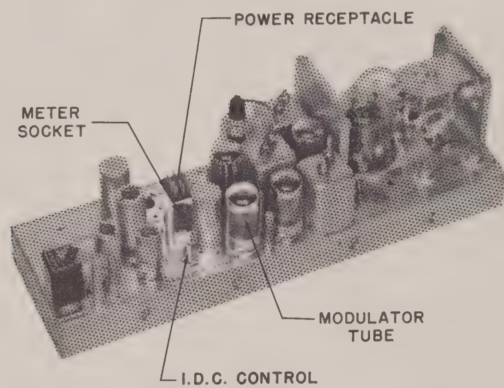
AM Sidebands

Figure 9A shows the relationship which exists between carrier and sidebands for amplitude modulation. The relative amplitude is plotted vertically and the frequency, horizontally. The carrier frequency is in the middle, with sidebands on either side.

Amplitude modulation produces only one pair of sidebands for any one modulating signal. For an audio signal of 5 kc and a 1000-kc RF, sidebands appear at 995 kc and 1005 kc. Where more than one audio signal (frequency) is

present, each will produce an additional pair of sidebands in the same manner.

In AM systems, modulation adds additional power which appears in the sidebands. Carrier power, however, remains unchanged. Amplitude changes in the audio signal do not alter the frequency, but the total amplitude is varied. The additional energy of the sidebands thus increases the total transmitted energy. This gives rise to the name "amplitude modulation."



This Photo of a Typical Motorola Transmitter Shows the Location of the Phase Modulator Components.

FM Sidebands

In frequency modulation the conditions are somewhat different. Let's start with the unmodulated carrier (figure 9B), again plotted vertically to indicate amplitude. When the carrier is modulated, only one pair of sidebands may be produced (figure 9C) and for an audio frequency of 5 kc, the sidebands are 5 kc above and below the carrier, as in AM. (Actually there may be more sidebands than shown, but the others are too low in amplitude to be significant.)

Compared to figure 9A, however, this significant difference exists: in FM the total transmitted power does not change when the carrier is modulated. The power for the sidebands is effectively "borrowed" from the carrier. Regardless of the degree of modulation, the total transmitted power remains constant.

In figure 9D, four pairs of side bands have been generated. The audio frequency is still 5 kc, but the audio has greater amplitude, resulting in greater deviations: hence, more sidebands are present. The sidebands are 5, 10, 15, and 20 kc above and below the carrier, the 5-kc spacing resulting from the 5-kc audio signal. Thus, the total bandwidth extends from 20 kc above to 20 kc below the carrier, for a total bandwidth of 40 kc. Again the total power does not vary; energy is shifted from the carrier to the sidebands.

The actual number of sidebands can be determined from the Modulation Index. The value of this index depends upon the amount of deviation and the audio frequency. The modulation index (M) is equal to the deviation divided by the frequency of the audio signal (M=Deviation ÷ audio frequency). Once the index is known, the number of sidebands and the bandwidth may be found from figure 10, which shows the number of sidebands and total bandwidth for the more common values of modulation index.

Suppose in figure 9C the audio frequency is 5 kc and the deviation is ± 2 kc. Using the above formula, the index is calculated to be 0.4. Figure 10 shows that there is only one pair of significant sidebands for this index. With a frequency spacing of 5 kc, the total bandwidth will be 10 kc. This is considerably wider than might have been supposed from a deviation of ± 2 kc, a deviation bandwidth of only 4 kc.

In figure 9D, let us assume a deviation of 10 kc, caused by a stronger audio signal but having the same frequency of 5 kc. The modulation index is calculated (by the formula) to be 2. The chart of figure 10 indicates 4 pairs of significant sidebands. The third column of the chart tells us that the bandwidth is 8 times the audio frequency, and 8 times 5 kc is 40 kc. (This is the same as shown in figure 9D.) The difference between 9D and 9C is the greater deviation in 9D, which in turn increases the modulation index and the number of significant sidebands.

Frequency modulation receives its name from the frequency distribution of the carrier energy upon being modulated. The total power always remains the same, but the energy is varied "frequency-wise" according to the audio signal. The patterns of figures 9C and 9D are constant only if the audio signal itself has a constant frequency and a constant amplitude. Otherwise the patterns are continually varying, according to the changing values of audio amplitude and frequency.

4. See TM 11-668 FM Transmitters and Receivers, pages 16-28; also FM Transmission and Reception, by Rider and Uslan, pages 33-46.

STUDENT NOTES

STUDENT NOTES

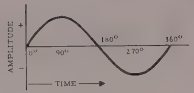


FIGURE 1A

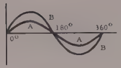


FIGURE 1B

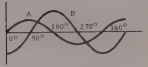


FIGURE 1C

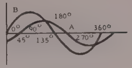


FIGURE 1D

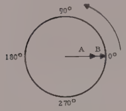


FIGURE 1E

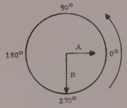


FIGURE 1F

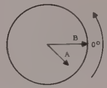


FIGURE 1G

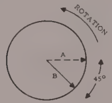


FIGURE 2A

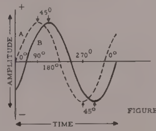


FIGURE 2B

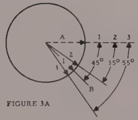


FIGURE 3A

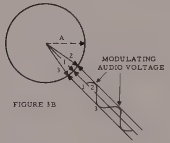
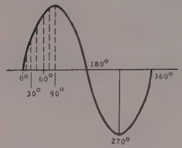


FIGURE 3B



ANGLE	% of MAXIMUM
0°	0%
15°	26%
30°	50%
45°	70%
60°	87%
75°	97%
90°	100%

FIGURE 4A

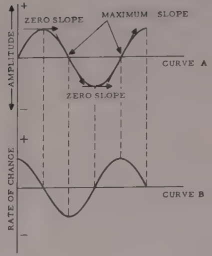


FIGURE 4B

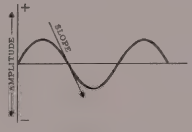


FIGURE 5A

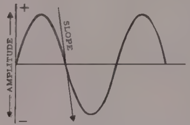


FIGURE 5B

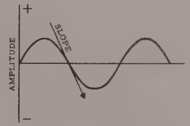


FIGURE 6A

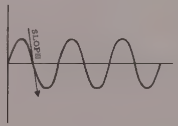
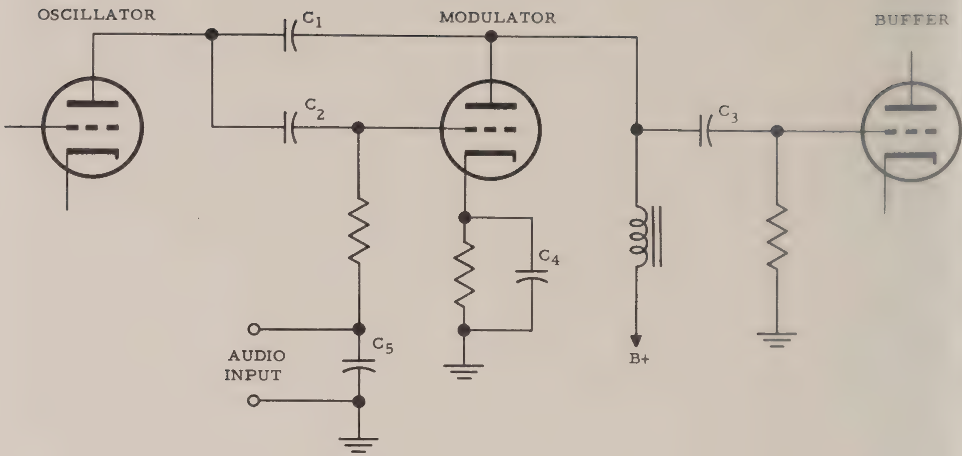


FIGURE 6B

STUDENT NOTES



PHASE MODULATOR
FIGURE 7

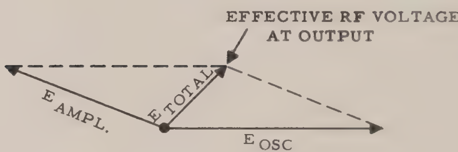
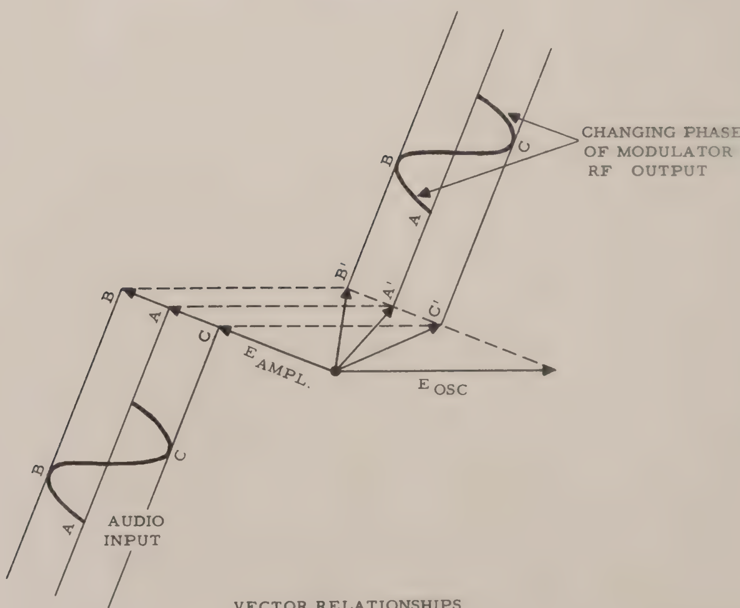


FIGURE 8A



VECTOR RELATIONSHIPS
OF PHASE MODULATOR
FIGURE 8B

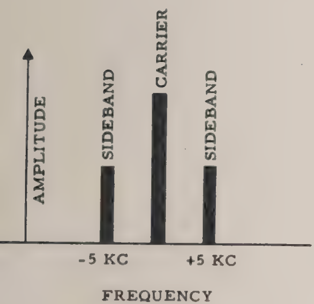


FIGURE 9A

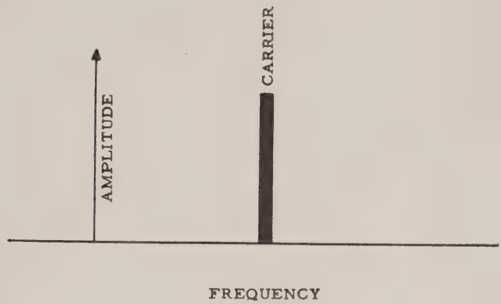


FIGURE 9B

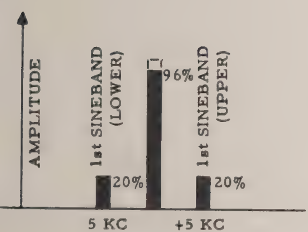


FIGURE 9C

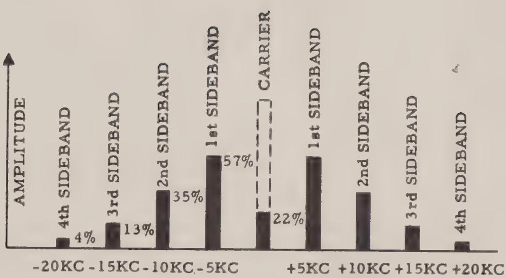


FIGURE 9D

BESSEL FUNCTION CHART

MODULATION INDEX (M)	NUMBER OF SIGNIFICANT PAIRS OF SIDE BANDS	BANDWIDTH REQUIRED (f=AUDIO FREQUENCY)
0.01 to 0.09	1	2f
0.1 to 0.4	1	2f
0.5	2	4f
1.0	3	6f
2.0	4	8f
3.0	6	12f
4.0	7	14f
5.0	8	16f
6.0	9	18f
7.0	10	20f
8.0	12	24f
9.0	13	26f
10.0	14	28f

M = deviation ÷ audio frequency

FIGURE 10

national
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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-4
FM TRANSMITTERS

The Audio Circuit: Deviation Control

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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-4
FM TRANSMITTERS

The Audio Circuit: Deviation Control

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

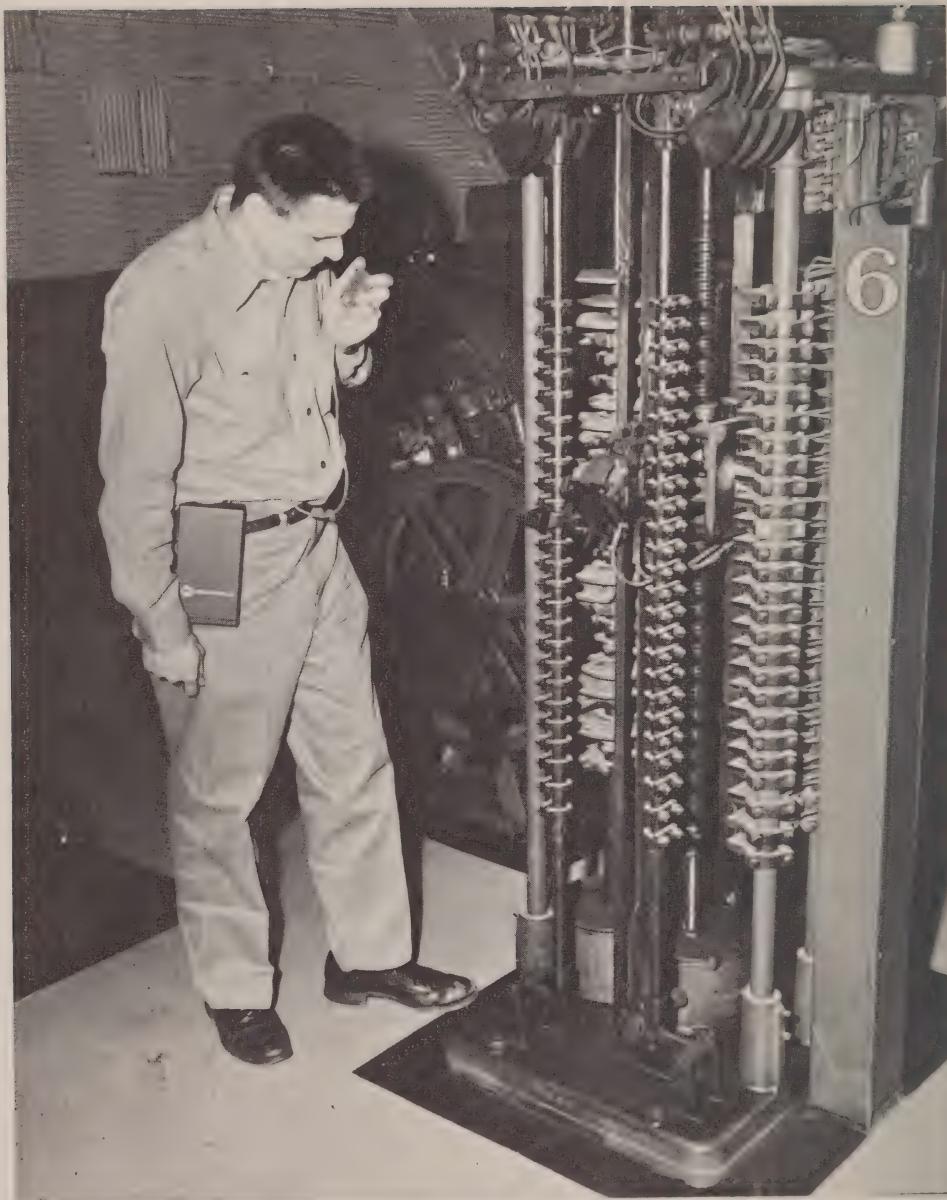
THE AUDIO CIRCUIT; DEVIATION CONTROL

LESSON TA-4

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.



Coordination of skilled personnel in large office buildings is another use of the "Handie Talkie" Pocket Transmitter and Receiver. Here an elevator maintenance man communicates with his partner in the elevator cage floors below.

THE AUDIO CIRCUIT; DEVIATION CONTROL

Lesson TA-4

Introduction

The preceding lesson described the operation of the phase modulator stage of the FM transmitter: we saw how the audio signal produces frequency modulation at the modulator output and we learned that the amount of deviation is determined by both the audio frequency and the audio amplitude.

The first step toward deviation control, then, must be to limit the amplitude of the modulating signal. Amplitude control by itself, however, is not enough. Normal voice signals, for example, have high-frequency components which, if allowed to reach the phase modulator, will cause excessive deviation. Thus, the second requirement is to include some arrangement which "molds" the audio waveform reaching the modulator.

While deviation control is perhaps the principal function of the audio section of the transmitter, some amplification of the small voltages from the microphone must be provided. We shall start our discussion of the transmitter audio section with the clipper stage.

The Clipper

The first step in deviation control is to limit the signal amplitude, usually by means of a "clipper" circuit. Both the positive and negative peaks are suppressed or "clipped" and are missing from the output waveform---see figure 1. The output waveform depends upon both the signal amplitude and the clip level. Where only a small portion of the wave is removed, the output waveshape resembles a trapezoid. If the input amplitude is very high the output becomes more like a square wave. For signals not exceeding the clip level, the clipper is inoperative and the input waveform is duplicated in the output.

A simple clipper circuit is shown in figure 2. Two diodes, parallel to the signal line, limit the amplitude of the output. The first diode is biased with its cathode positive to ground and this tube is non-conductive until the positive peaks exceed the bias voltage. The tube then conducts and limits the amount of positive voltage that can appear at the output terminals. The second diode has its plate biased negatively to ground and will not conduct until the cathode becomes more nega-

tive than the plate. On the negative half cycle, peak voltages exceeding the plate bias are clipped by the second diode. Thus, the diodes are able to maintain a constant-amplitude output in spite of an increasing input. The amount of output voltage is limited to the bias established on the diodes.[1]

The First Step in Controlling Deviation is to Limit the Amplitude of the Audio Wave.

In the preceding phase modulator lesson, we found that the deviation is determined by the rate of change of the audio signal and the maximum rate of change occurs when the audio voltage is passing through its zero value. Referring again to figure 1 of this lesson, by clipping the peaks from the wave, the rate of change of the waveform at its zero points is not altered. Thus, there is no improvement (control) of the resulting deviation. The clipped wave cannot yet be applied to the phase modulator---there must be some further control of the waveshape.

INTEGRATION

Before the clipped wave can be applied to the phase modulator, it must be integrated. Figure 3 shows an integrator circuit and some typical waveforms. The integrator consists of a resistor and a capacitor connected in series with the source, with the output taken from across the capacitor. Integration changes a square wave (A) or a trapezoidal wave (B) to a triangular output. A sinewave voltage (C) applied to the input, however, produces a similar waveform at the out. Thus, the waveshape is altered by integration only when the input is other than a sinewave.

The output waveform depends not only on the type of applied pulses, but it also depends on (1) the duration of the applied voltage and (2) the time it takes for the capacitor to charge and discharge.

The integrator of figure 3 is included in the circuit of figure 4. Here we have added the necessary circuitry to charge and discharge the capacitor. Assume that the battery voltage is 100 volts. Be-

1. See TM 11-672 Pulse Techniques, pages 12-16 and pages 20-26.

cause the capacitor and resistor are connected in series across the battery, the sum of their two voltages must equal the battery voltage.

At the instant that switch S1 is closed, the full battery voltage is applied to the resistor and there is no charge (voltage) across the capacitor. This condition is momentary, however, for the current charges the capacitor and a voltage is thus established. The polarity of this capacitor voltage is in opposition to the applied (battery) voltage, so the effective applied voltage is now less than 100 volts.

With lower applied voltage the current is less and the voltage across the resistor decreases. Although the current gradually decreases, it continues to charge the capacitor until the voltage across the capacitor is equal to the full battery voltage. Once the capacitor is fully charged there is no action (current) in the circuit. Without circuit current, the voltage across the resistor is zero.

The manner in which the capacitor and resistor voltages change is shown in the two graphs of figure 4. Regardless of the amount of applied voltage or the values of R and C, this pattern is always the same. The only variation is in the rate at which the capacitor charges. This, in turn, depends upon the "time constant" of the two units and is determined by the values of R and C. The product of the resistance in ohms and the capacitance in farads is equal to the time constant (TC) in seconds: $TC = R \times C$. In practice, the units can be changed to megohms and microfarads without affecting the results.

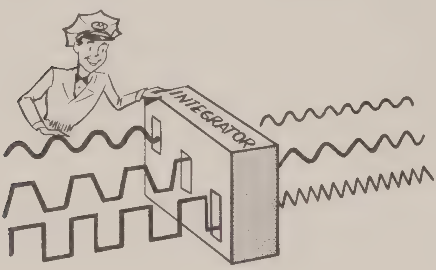
For a practical illustration of time constant, let R in figure 4 be equal to 1 megohm and C to 1 microfarad. The time constant (TC) is 1 X 1 or 1 second. For our example, then, the "time period" will be 1 second. This time period indicates the amount of time it takes for the capacitor to charge to 63% of the applied voltage. Now lets see how this applies to figure 4.

In the graph showing the capacitor voltage, the first time period extends from the left side of the graph (the instant that the switch is closed) to point "1t". During this time period (one second for our example), the capacitor charges to 63 volts (63% of the 100 volts applied by the battery).

During this same time period, the voltage across the resistor decreases from 100 volts to 37 volts. With the capacitor charged to 63 volts, the acting voltage in the circuit is only 37 volts. During the second time period, the interval between 1t and 2t, the capacitor again charges 63% of the effective circuit voltage, which in this case is 63% of 37 volts. Thus, at the end of two seconds the charge on the capacitor is 87 volts.

At the end of three time periods the capacitor has a charge of 95

volts, and in 4 time periods the charge is 98 volts. The capacitor theoretically never reaches the full 100 volt charge of the battery, but after 5 time periods the charge is 99 volts and for all practical purposes we consider the capacitor to be fully charged. The resistor voltage has decreased to only 1 volt during this time. We are concerned with only the capacitor voltage, however, for this is the output of the integrator.



As Part of the Complete Process of Deviation Control, the Integrator Changes Square Waves into Triangular Waves-- Sinewaves are Unaffected.

After the capacitor is fully charged there is no further action until some provision is made for its discharge. This is done by opening S1 and closing S2. The capacitor now becomes the source of voltage and it discharges through the resistor.

During the first time period the capacitor discharges 63%----after the first second only 37 volts remain. During each successive time period the capacitor loses 63% of the remaining charge until after 5 time periods, when the capacitor is considered to be fully discharged. The applied voltage in figure 5 may be the result of opening and closing the switches of figure 4 or it may be an applied rectangular of square wave.

In figure 5 the input voltage is applied for a relatively long time ---long enough for the capacitor to fully charge and discharge. The time constant of the RC circuit is short compared to the time duration of the applied voltage. This is not a representative situation, however, for an integrator normally has a long time constant, usually about ten times longer than the time duration of the applied pulse. (When we speak of a "long" or a "short" time constant we are always referring to the time constant of the circuit as compared with the time duration of the applied voltage.) The time required for the integrator capacitor to charge and discharge is then considerably longer than the time duration of the applied voltage.

Figure 6 shows the normal operation of an integrator circuit. The duration of the applied voltage is short compared to the time it takes for the capacitor to charge and discharge. For convenience, only two pulses of applied voltage are shown during the first time period. In practice, however, ten or more of these pulses will occur during each time period.

With the applied voltage present for such a short time, the capacitor charges only a small amount

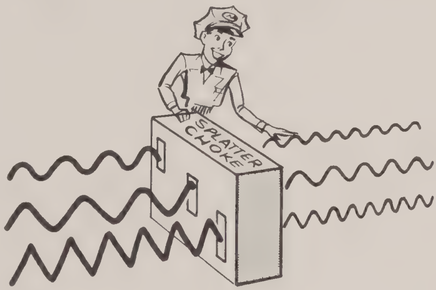
before the applied voltage is removed and the capacitor must discharge. The output voltage has a low amplitude as compared to the input. More important, however, is the change in the output waveform. The capacitor charge and discharge, occuring over the straight portion of the curve, has produced a wave form which is nearly triangular.[2]

Assuming that the pulse rate and duration are constant, the amplitude of the output voltage is determined solely by the amplitude of the applied signal. The clipper which precedes the integrator prevents the input from exceeding a certain value, so the integrator output is thus controlled. And, since the slope of the output waveform cannot exceed that of the triangular wave, the integrator output, when applied to the phase modulator, cannot produce excessive deviation.

Choice of R and C in the Integrator

There are many values of R and C which may be used to obtain the same time constant, and the choice of a large R and a small C or a large C and a small R is determined by the circuit requirements. With a large value of resistance the current in the circuit is small and the charge or voltage across the capacitor is low. The charging rate of the capacitor will be quite linear, however, and the output will be a triangular wave.

If a small value resistor is used, the larger current produces a greater voltage across the capacitor. As a result of this higher capacitor charge the waveform may tend to be curved. Thus, the final choice of R and C must be a compromise between linearity and amplitude of the output waveform.



The Splatter Choke Smoothes Out the Sharp Corners of the Triangular Wave so that the Modulating Signal is More Sinusoidal.

If a sinewave signal into the clipper is lower than the designed clip level, the input to the integrator and the output signal have a similar waveshape. Input signals receiving partial clipping result in trapezoidal waves from the clipper and, while they resemble a triangular waveform at the integrator output, their waveshape is actually more rounded at the peaks and correspond more closely to the sinewave. Strong input signals, which are changed to square waves by the clipper, become triangular waves at the integrator output. Thus, the deviation control circuit reacts only when the signal amplitude is so high that it would cause

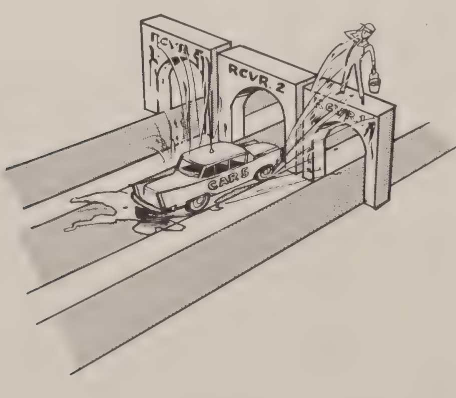
2. See TM 11-672 Pulse Techniques, pages 5-10.

too much deviation if applied directly to the phase modulator.

Splatter

Although the harmonic content of a triangular wave is an improvement over the square wave for modulation purposes, there is some remaining distortion in the nature of odd harmonics. And, if the triangular wave with its sharp peaks is applied to the phase modulator, there will be energy outside the intended bandwidth of the transmission.

These unwanted deviations far from the channel frequency are commonly referred to as splatter and they cause undue interference in the adjacent and alternate channels. Splatter makes narrow-band operation impractical. It is thus desirable to further control the waveshape of the modulating signal.



Without Deviation Control "Splatter" from One Channel May Interfere with Adjacent Channels.

In figure 7, coil L and the capacitor at the output smooth out any sharp "corners" of the signal so that the final modulating voltage appearing across the capacitor more closely resembles a sinewave.

The coil opposes all sudden changes of current, with the result that the output waveform developed across the capacitor is less triangular. Because the waveshape more closely resembles a sinewave, the harmonic content has been reduced. The resulting deviation at the phase modulator is now further controlled and is limited to the intended bandwidth of the system.

The value of the coil and capacitor are chosen so that the output voltage decreases rapidly beyond 3000 cps. The attenuation is greater than 12 db per octave and is in conformity with the FCC regulation for all new transmitters placed into operation. The capacitor also serves as an RF bypass for the circuit and prevents high-frequency noise and other undesirable voltages from reaching the modulator grid. The resistor across the output terminates the audio filter and also provides the DC ground for the modulator grid circuit.

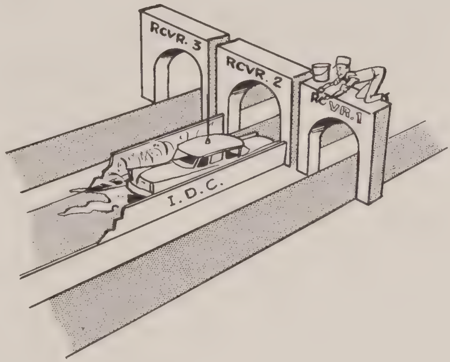
Because of its action is reducing splatter, it is logical that coil L of figure 7 should be called the "splatter choke." In operation, it is a waveshaping element which reduces the harmonic content of non-sinusoidal signals.

Instantaneous Deviation Control

The basic principles of deviation control have been discussed in the preceding pages, and figure 7 is a typical circuit. Its main advantages are its simplicity, its economy of parts, space and weight, and its low power consumption. In addition, the action is instantaneous and allows close speaking into the microphone without overloading or paralyzing the circuit. Motorola has adopted the name "Instantaneous Deviation Control" for this circuit.

Microphone voltage is applied to the grid of the first stage through a conventional capacitor-resistor combination. The first stage uses a pentode type high-gain voltage amplifier tube and conventional circuitry usually found in any high-gain audio stage. A small capacitor (C1) between the grid and cathode effectively shorts out unwanted high-frequency inputs. The amplified signal from this stage is applied to the clipper.

The clipper-limiter stage consists of two diodes, each with its own resistor between cathode and ground, but with a common plate resistor. The signal is applied to the cathode of the first diode and the output is obtained from the cathode of the second diode. In analysing the operation of the clipper we shall be interested in (1) the voltage variations at each cathode, (2) the cathode-plate voltages, (3) the instantaneous voltages at the plates, and (4) the output voltage.



"IDC" Prevents Splatter from One Channel to Another.

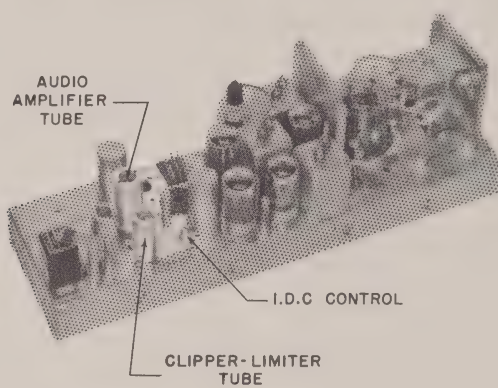
When the incoming signal swings positive, it raises the cathode voltage of the first diode and the plate-cathode voltage decreases. As a result, the plate current decreases. This makes the plate of the second diode more positive and there is an increase of voltage (and current) between the plate and the cathode of the second diode. This increased plate current in the second diode raises the voltage across the cathode resistor at the output. Capacitor C2 at the output charges positively, providing a duplication of the input waveform during the positive half cycle.

The output waveform, however, duplicates the input signal only up to the point where the applied signal is sufficiently strong to drive the first diode to plate current cutoff. When the cathode potential of diode D1 increases to the point where its effective plate-cathode

voltage is very small, the plate current approaches zero. There can be no further change in the voltages and currents---the diode currents remain the same and the output is maximum. This results in a limiting (or clipping) of the positive peaks in the output when the input reaches a certain level.

"clip level." When the plate-cathode voltage of diode 2 approaches zero, the plate current is at the point of maximum possible change. Signals beyond this level encounter a clipping of the negative peaks.

The change of internal resist-



This Photo of a Typical Motorola Transmitter Shows the Location of the Audio-IDC Components.

When the incoming signal swings negative, the cathode of the first diode is made negative (less positive) and the effective plate-cathode voltage increases, resulting in an increase in plate current. This increases the voltage drop across the common plate load resistor and the plate potential of the second diode is lowered. The plate-cathode voltage of diode 2 is now lowered and the plate current must also decrease. With the consequent decrease of cathode voltage, output capacitor C2 now assumes a negative charge.

The output will be an exact reproduction of the negative input until the input voltage reaches

ance for the condition of being in clip or not in clip is of particular importance to the operation of the circuit. While it is not immediately obvious, the internal resistance of the diodes is in series with output capacitor C2, and together these units make up the integrator.

When the input signal is small and does not drive the diodes into clip, the internal diode resistance is small and the integrator time constant is short. It is not desirable to have integration for this signal, however, for there has been no clipping.

When a strong signal drives the diodes into clip, the internal tube

resistance is high and the time constant of the integrator is normal. As a result the waveforms are integrated to a more suitable output.

The signal from the integrator has its waveform altered further by the splatter choke(L). The output voltage is more sinusoudal and does not overdeviate the transmitter.

The potentiometer allows for the proper level of audio signal to be applied to the modulator. This pot is termed the deviation "control." The adjustment of this pot is critical and is never indiscriminately "turned" by the trained technician---it is essential to follow the recommended procedure in order to insure its correct adjustment.[3]

Overall Effect of IDC

As far as the transmitter is concerned, the IDC (Instantaneous Deviation Control) circuit limits the deviation to the assigned channel; splatter into the adjacent and alternate channels is greatly reduced. This makes it possible to utilize to a greater degree the frequencies assigned to two-way communications. Because the transmission bandwidth is now controlled and maintained within a narrow band, more channels with closer spacing are possible.

As far as the transmitted message is concerned, IDC introduces no appreciable loss of intelligibility---the distortion is well within 10%. In two-way communications we are interested in crisp, clear messages, not in "high-fidelity."

Although voice waveforms are quite jagged in appearance, and bear little resemblance to the sine-wave pattern we have been studying, they pass through the IDC circuit with little change in intelligence---they are reproduced at the receiver with sharp clarity.

The average voice level between syllables is comparatively low and experiences little or no clipping. With IDC it is possible to provide greater deviation for weaker audio inputs and a higher average deviation without exceeding the authorized limits. Since all input voltages cause near-maximum modulation, the signal-to-noise ratio is improved. This improvement is particularly noticeable in fringe or weaker signal areas.

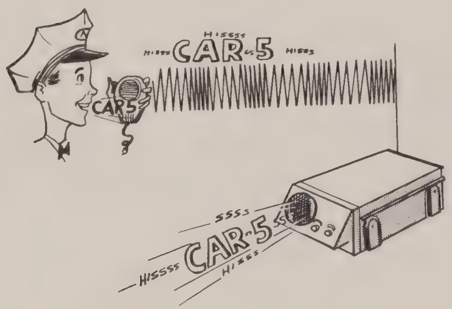
The Motorola IDC circuit does not have any delay in attack time, nor is there any paralysis from transients. The action is instantaneous.

Microphone Circuit

The audio circuit of most Motorola transmitters operates with an input of either one-fourth or one-fifth volt. Unless the microphone provides this value of input, additional amplification (preamplifier) is necessary.

3. See "Instantaneous Deviation Control," reference T-4.

While the carbon microphone requires a source of DC voltage and leaves something to be desired as far as frequency response is concerned, it can be used without separate amplification and its operation is satisfactory for most voice purposes. Its high output voltage makes it practical for mobile service in particular.



The Carbon Microphone is Noisy and has a Characteristic "Hiss." In Addition, its Frequency Response is Poor.

Figure 8 shows a typical carbon microphone circuit. The dropping resistors in series with the microphone reduce the B supply voltage to about 3 volts at the mike and the current to about 10 ma. Alternate taps permit using carbon microphones having different output levels. At the lower tap, (position 2) the full mike output is connected into the audio grid. This is used for carbon microphones having a lower output voltage. Microphones with higher outputs use the connection at the upper terminal (position 1) and only part of the mike output is applied to the audio amplifier grid. This insures a constant input to the audio stage regardless of which mike is used.

The carbon microphone has several disadvantages. The DC current in the mike generates noise which is amplified along with the desired signal, and this noise may become noticable in relatively quiet installations. Even if it is not particularly bothersome, this noise decreases the desired modulation and lowers the effective signal-to-noise ratio.

Another disadvantage of the carbon microphone is its limited frequency response. Even though the only reproduced message is a small bnad of frequencies between 300 and 3000 cps, the clarity is impaired somewhat because of frequency distortion.

The principal reason that the carbon microphone has had such popularity for many years has been the absence of something better for a practical application in mobile use. To meet the demands of the modern two-way system, however, it is necessary to achieve the best response possible. This leads us to a consideration of the transistorized microphone.

Transistorized Microphone

The newly-developed transistor provides an ideal solution to the mike problem. The low power drain and compact circuitry of the transistor make it possible to build a small preamplifier stage right into the mike housing. It is

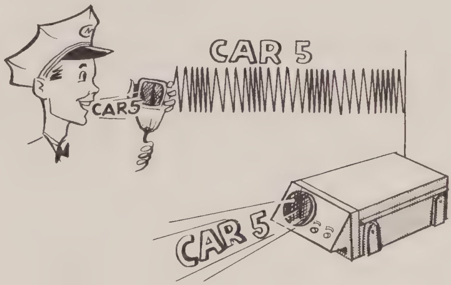
thus possible to use a dynamic microphone with its superior frequency response and, by means of the transistor amplifier stage, provide sufficient voltage at the transmitter input.

Motorola has developed a compact dynamic microphone which incorporates a stage of transistor amplification right in the mike housing. The low output voltage of the dynamic microphone is amplified at the mike and built up before any outside noise pulses can be introduced. Besides its advantage of improved frequency response, this arrangement avoids nates the noise inherent to the carbon microphone.

The superior performance of the transistorized microphone improves the clarity of the receiver output and provides more intelligable messages in weak signal areas. The clear, crisp voice reproduction is particularly appreciated when there is a high noise level competing with the message, as when a car or truck is traveling at high speed with the windows open.

Besides its advantage of better reproduction, the transistorized microphone is directly interchangeable with the carbon microphone. The DC supply required for the carbon element becomes the supply for the transistor amplifier stage.

Figure 9 shows a transistor microphone amplifier stage. This amplifier provides gain the same as a vacuum tube amplifier, and the output is applied to the grid of the audio amplifier (figure 7) in the same way. The relatively low output impedance (about 500 ohms) is not subject to a lot of noise pick-up in the mike cabling.



The Transistorized Dynamic Microphone has Excellent Frequency Response and is Very Quiet.

Speaker-Microphone Combination

By using a small dynamic speaker element with a transistorized stage of amplification for the microphone, it is possible to have a speaker and microphone in one unit. The speaker element is usually about 50 ohms and operates well, both as a speaker and as a mike. The advantage is that the unit can be held close to the ear when the surrounding noise level is high. It also provides a certain amount of private listening when used in this manner.

The circuit of the speaker-microphone is shown in figure 10. The transistor preamplifier cir-

cuit (shown as a block) is the same as given in figure 9. It is necessary to use a small impedance-matching transformer (T1) to match the 3-ohm impedance of the voice line, coming from the receiver, to the 50-ohm speaker.

With the switch in its release position (as shown), the audio from the receiver feeds into the speaker through T1 and the switch. When the switch is depressed (by the operator), the speaker (now the microphone) is connected into the preamplifier. At the same time, the switch completes the ground circuit to the push-to-talk relay and the relay closes, placing the transmitter in operation.

STUDENT NOTES

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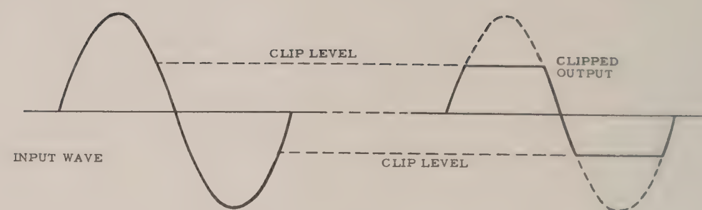
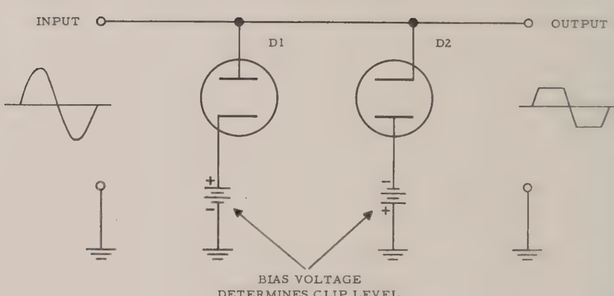
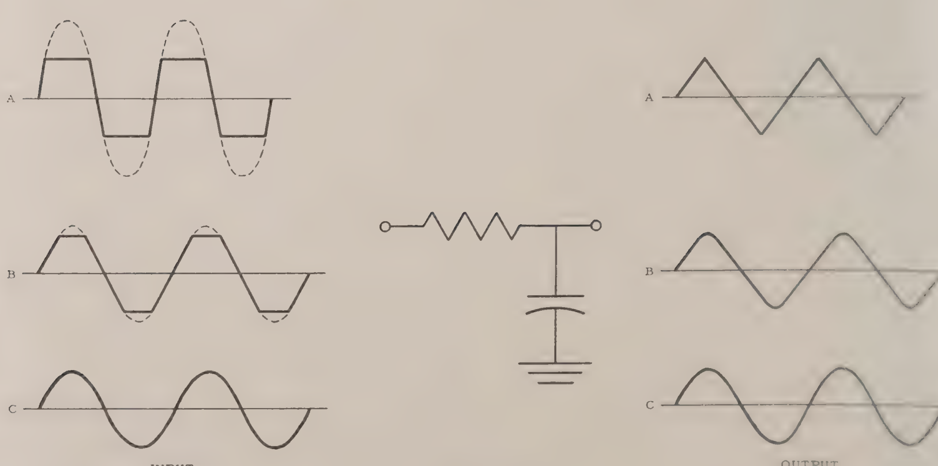


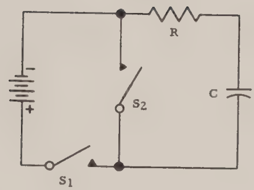
SINE WAVE CLIPPING
FIGURE 1



DIODE CLIPPER
FIGURE 2



INTEGRATOR
FIGURE 3



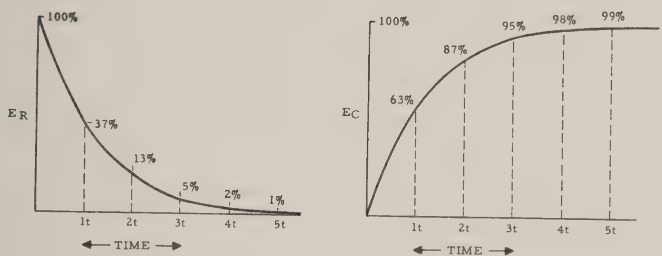
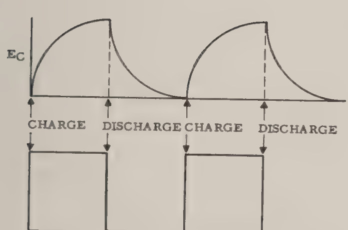
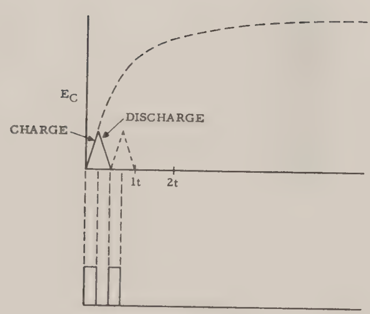


FIGURE 4

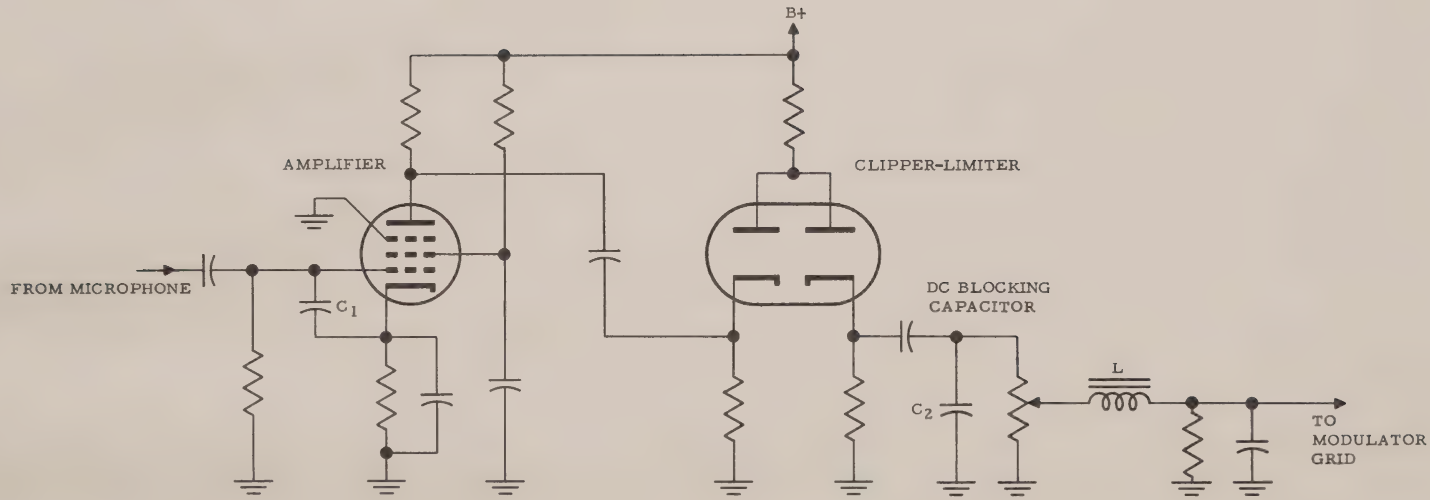


INPUT VOLTAGE
RC = SHORT TIME CONSTANT
FIGURE 5

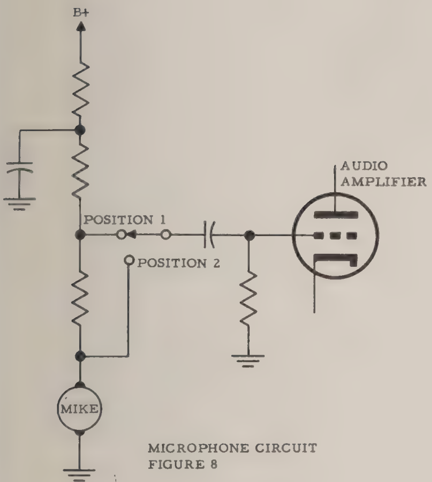


INPUT VOLTAGE
RC = LONG TIME CONSTANT
FIGURE 6

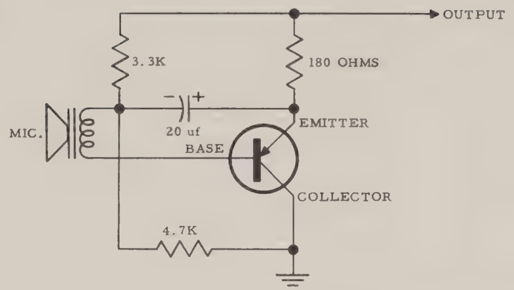
STUDENT NOTES



TRANSMITTER AUDIO SECTION
FIGURE 7



MICROPHONE CIRCUIT
FIGURE 8



TRANSISTORIZED
MICROPHONE AMPL.
FIGURE 9

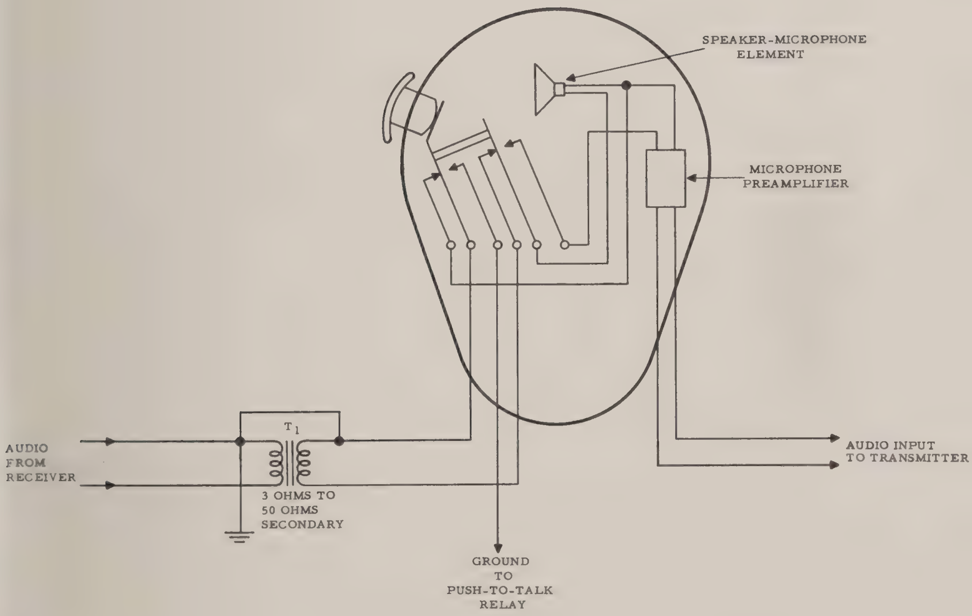


FIGURE 10

national

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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-5
FM TRANSMITTERS

Frequency Multiplication

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-5
FM TRANSMITTERS

Frequency Multiplication

—one of a series of lessons on two-way FM communications—

MOTOROLA **TRAINING INSTITUTE**
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

FREQUENCY MULTIPLICATION

LESSON TA-5

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Road construction crews, supervisors and foremen make use of two-way radio to control the various projects in their area of operation. Tax payers' money is saved through this increased efficiency.

FREQUENCY MULTIPLICATION

Lesson TA-5

Introduction

We found in our study of the block diagram that the low-frequency oscillator and phase modulator of the FM two-way communications transmitter are followed by a series of frequency multipliers and that this multiplication is necessary in order to provide a signal at the channel frequency. In addition to multiplying the frequency, these stages also (1) increase the deviation by the same factor and (2) supply a progressively greater amount of power from stage to stage so that the output of the last multiplier is sufficient to properly drive the final amplifier.

Requirements for Frequency Multiplication

The frequency multiplier is often called a harmonic generator or a harmonic amplifier. Both names are descriptive, for the stage operates both as an amplifier and as a harmonic generator. Efficient operation of the frequency multiplier depends upon the following requirements:[1]

1. There must be sufficient drive from the preceding stage. Without a strong grid drive the harmonic content in the output will be low.

2. For efficient operation, grid-leak bias is used to establish Class C operation. The grid bias for the frequency multiplier is often greater than the bias which is used for regular Class C operation.

3. The duration of the plate current pulse must be short compared to the complete cycle of input voltage. The actual duration of the pulse is a compromise between the efficiency associated with a short pulse and the power provided by a longer pulse.

4. For a strong harmonic output the plate tank must have a high Q and the loading effect of the grid circuit of the following stage must be taken into consideration.

Grid Bias

Figure 1 shows a typical frequency-doubler circuit. The stage is operated in Class C, making it possible to take advantage of the

1. See FM Transmission and Reception, pages 81-83.

high harmonic content present in the plate circuit when the grid is biased beyond cutoff.

Class A and Class B Operation Has Many Losses; Only a Small Portion of the Input Power Reaches the Output.

Grid-leak bias is used almost exclusively to obtain Class C operation in multiplier stages. Only where the tube is a high-power type is it necessary to include protective bias. When protective bias is used, it is secured from a fixed source of negative DC voltage. This minimum fixed bias limits the plate current to a safe value in case the grid excitation should fail. (More will be said about this later in the lesson when we discuss the Doubler-Driver.)

Grid-leak bias operation in the multiplier stages is the same as that described for the limiter circuit in the receiver section. To provide a strong harmonic content, the bias is greater than that normally used for a straight Class C amplifier. The input signal must have considerable amplitude in order to produce a large bias.[2]

2. See TM 11-668, pages 66-68.

Plate Current Pulse

Because of the high negative bias on the grid, plate current occurs only during a small portion of each cycle of input voltage and consists of a series of short pulses, one for each input cycle. Only when the grid is on its positive excursion and overcomes the bias can there be plate current.

These short pulses of plate current are desirable, for the shorter the pulse the greater is the efficiency; the harmonic content increases as the pulse becomes shorter. There is a practical limit, however, as to how short the plate pulse may become, for the total power available in the plate circuit is limited by the amplitude and duration of the pulse. If the pulse becomes too short the power decreases, even though the plate efficiency increases.

Thus the final plate-current pulse must be a compromise between efficiency (for the best harmonic content) and power output.

Because the plate current pulse is not a sinewave, it is rich in harmonics. In order to establish an output voltage at the desired harmonic frequency, it is necessary to include an efficient tuned circuit which captures maximum energy at the desired frequency. Other frequencies, however, encounter a low impedance and produce very little voltage across the tank. In fact, to establish a

signal at the next stage which is relatively free from these undesired harmonics, it is customary to use a transformer arrangement between the stages, with the secondary, as well as the primary, tuned to the desired harmonic.

In the frequency doubler, figure 1, the plate tank is resonant to twice the frequency of the grid circuit, and the tuned plate circuit smooths out the pulses of plate current into a sinewave voltage. It might be well to inspect the operation of this plate tank.[3]

The Plate Tank Action

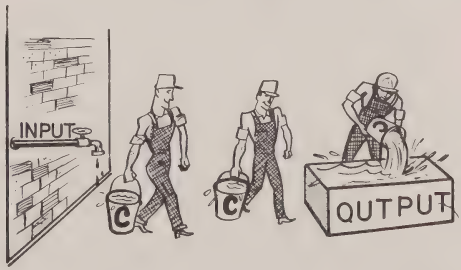
Almost every electronics technician has wondered, sometime in his career, how a tuned circuit is able to produce a sinewave from a short pulse of energy. This action has been aptly compared with the pendulum of a clock and with the vibration of a tuning fork, but for our analogy we shall liken it to a child's swing moving back and forth.

Most of us have pushed some youngster in a swing, perhaps to the tune of "Higher, daddy!" In the swinging action, energy is continually transferred back and forth between that of position (potential energy) to that of motion (kinetic energy). When the swing reaches its highest point it is momentarily motionless, but because of its position it soon swings down to its lowest point and up to a high position again. If no additional energy is added, the swing continues in this manner for a considerable time, but the motion gradually decreases and the swing finally comes to a stop.

All that is needed to keep the swing in motion is an occasional push. This need not be a continuous push; it may occur once during each complete swing, or even during each second or third swing. To keep the swing in motion it is necessary only to replace whatever energy may be lost in the swinging action.

The tank circuit operates in much the same manner as the swing. A transfer continually takes place from potential energy to kinetic energy.

If a charged capacitor is placed across a coil, the latter provides a discharge path for the capacitor and the resulting current causes a magnetic field to build up around the coil. When the current decreases (as a result of the capacitor being discharged), this magnetic field collapses and induces a voltage in the coil.

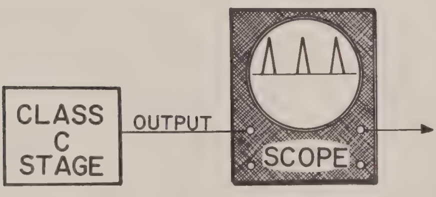


In Class C Operation the Stage Losses are Reduced and there is Considerable More Output for a Given Input.

3. See TM 11-662, pages 176-177; also TM 11-668, page 68.

This voltage maintains the current and once more charges the capacitor, but this time in the opposite direction or polarity. The action is then repeated, this time with the capacitor discharging through the coil in the opposite direction.

If there were no internal losses in the coil and capacitor, this action would continue indefinitely. Due to resistive losses in the coil and dielectric losses of the capacitor, however, energy is used up and the circulating current gradually decreases. The resulting "damped" waveform shows a gradual decrease in amplitude.



In Class C Operation the Plate Current is a Series of Short Duration Pulses.

In order to maintain the circulating current at a constant value, all that is required is to supply the tank with sufficient energy to replace that which is lost. Again, this energy need not be supplied continuously, but may be done periodically in the nature of short pulses.

The effect of the action within the tank is to even the pulses over one or more complete cycles. If the Q of the tank circuit is at least 10, the waveform of the circulating current will be sinusoidal. The higher the Q of the tank, the higher will be the circulating current.

The duration of the plate current pulse is a vital factor in the efficient production of plate circuit harmonics. The higher harmonics require proportionally shorter pulses. The duration is usually measured in the number of degrees of each cycle during which plate current occurs.

For maximum output at the second harmonic, the duration of the plate current pulse may be as long as 120°, with a minimum of 90°; fifth harmonic operation requires plate current for only 60° of the entire cycle. Considering the fundamental (or first harmonic) power to be 100%, the maximum possible power at the second harmonic is only 65% and the fifth harmonic is as low as 20-25%. In order for a higher harmonic to develop the same output voltage, the impedance of the plate tank must be several times greater than that necessary for one of the lower frequencies.[4]

In receivers, where the power requirement is low and the main interest is the available voltage, it is practicable to use higher order harmonics between the oscillator and first mixer. In the case of transmitters, however, doublers and triplers are used more frequently than higher order multi-

4. See TM 11-681 Electrical Fundamentals, pages 97-106; also TM 11-668, pages 68-72.

pliers. Also, it is more difficult to develop a high-impedance tank circuit which is resonant to a higher frequency and still capable of handling appreciable power.

Impedance of the Plate Tank

The impedance of the plate tank not only affects the power available in the tank, but it also influences the transfer of power and the loading of the stage. In order to determine the impedance of the tank it is essential to understand the factors controlling the Q and the reactance of both the capacitor and the coil.

The opposition (reactance) offered by a capacitor to AC varies inversely with the frequency---as the frequency increases the reactance decreases, and vice-versa.

The formula for capacitive reactance is,

$$X_c = 10^6/6.28\ fc$$

(For convenience, 1,000,000 is written as 10^6.) In the formulas of this lesson the frequency (f) will be in megacycles, the capacitance (c) in micromicrofarads and the inductance (L) in microhenrys. As an example of capacitive reactance, the opposition offered by a 50 uufd capacitor at 3.5 mc is,

$$X_c = \frac{10^6}{6.28 \times 3.5 \times 50}$$

$$X_c = \frac{10^6}{1100} = 910 \text{ ohms}$$

This same capacitor has a reactance of only 91 ohms at 35 mc.

The Q or "figure of merit" of a capacitor is the ratio of its reactance to its RF resistance. As a formula, $Q = X_c/R$. There is no simple way of measuring the RF resistance (R). In order to insure a high Q, however, the capacitor is designed to offer very low resistance. The low resistance means a minimum of loss and consequently a high Q.

The reactance or opposition offered by a coil to AC current varies directly with frequency, and it is expressed by the formula,

$$X_L = 6.28 \times f \times L.$$

Example: the reactance of a 65 uh coil at a frequency of 3.5 mc is,

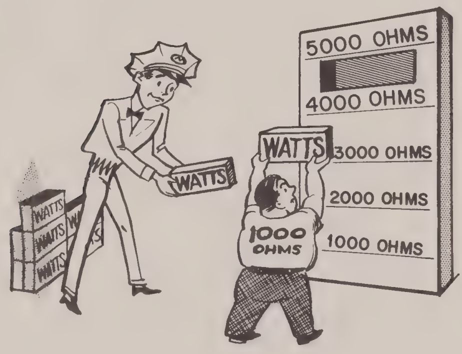
$$X_L = 6.28 \times 3.5 \times 65 = 1429 \text{ ohms.}$$

If the frequency is increased to 35 mc, the reactance increases to 14,290 ohms.

The Q of a coil, like that of a capacitor, is the ratio of its reactance to its RF resistance, Q =

X_L/R. Here again, the RF resistance must be minimized in order to insure a high Q.

The opposition to plate current offered by the resonant plate tank is maximum, and resistive in nature. At either side of resonance the circuit is reactive and the impedance is less than maximum. Inside the tank, however, the current encounters a series resonant condition, so the internal tank opposition is minimum and the tank current is maximum.



A Mismatch Between the Source and the Load is Not Conducive to the Transfer of Power.

The impedance (Z) of the parallel resonant circuit is approximately equal to the product of the Q and the reactance of either unit. As a formula Z (impedance) = QX. Thus, in order to have a high impedance it is necessary to have a high Q. The extent to which the impedance changes for off-resonance operation depends upon the Q. With a high Q, the impedance is large at resonance and the decrease from maximum impedance is rapid on either side of resonance. With a low Q, the resonant impedance is not as large but the decrease from maximum impedance on either side of resonance is more gradual.

When a load is connected to a tank circuit it absorbs energy from the tank, and the Q of the tuned circuit is lowered. The effect of the load is to increase electrically the internal resistance, which lowers both the Q and the impedance. Thus it is not enough, in design considerations, to know the unloaded Q of a tank circuit. It is equally important to determine the effect of the load upon the plate circuit impedance.

If a load which takes considerable power from the tank is purely resistive, it acts as if it were a resistor connected in parallel with the tank circuit. This is the case when the load resistance is lower than the tank impedance and the losses inside the tank are comparatively small.

L-C Ratio

The product of L-C for any given frequency is determined by the formula:

$$LC = \frac{25,281}{fr}$$

(f is in megacycles, L in microhenrys, and C in micromicrofarads as before.)

This formula shows that for any given value of L there is a capacitance value which will produce resonance. The circuit requirements determine whether a high value of L or a high value of C should be used. For power transfer, transmitter tank circuits usually require a large capacitance and a small inductance. This is known as a low-impedance tank, and the L/C ratio is low.

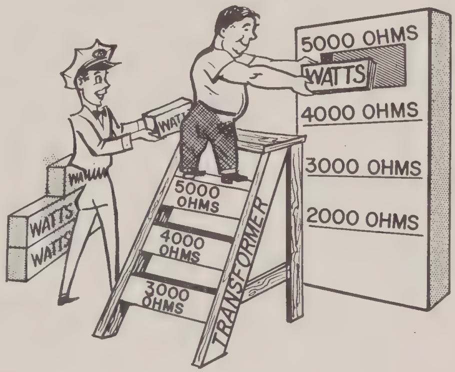
A low-impedance tank is necessary for an impedance match and gives the best performance for a heavily loaded tank. This combination also provides the best power transfer characteristics and discourages both the production and the passage of unwanted harmonics and spurious response. If the capacitor is made too large, however, the efficiency will be poor due to large circulating tank currents.

Where frequency multiplication is used, the plate tank must provide a high impedance and a high L is required. This provides a higher voltage at the secondary.

Grid Driving Power

Grid driving power is a term often encountered in connection with Class C amplifiers and frequency multipliers. It refers to the power absorbed within the grid circuit of any stage.

Transmitter tubes are capable of drawing considerable grid current when their grids are driven positive---the power dissipation may be appreciable. Grid driving power must be furnished by the plate circuit of the preceding stage; hence this power or "load" must be taken into consideration.

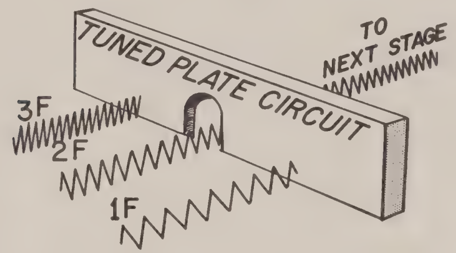


Maximum Power May be Delivered When the Impedances are Matched. Impedance Matching is Possible with a "Step Up" Transformer.

For trouble-free operation, the plate circuit of a tube should be capable of delivering several times as much power as that actually dissipated in the following grid circuit. Otherwise, as soon as the stage shows a decrease due to tube aging or some other common cause, the grid drive to the next stage is lowered and the power output of that stage shows a decided decrease. By providing "reserve" power, normal variations do not noticeably affect the over-all operation of the transmitter.

High Frequency Considerations

Besides the additional grid driving power required, there are many other power losses which are of no use to the desired output, but which must be taken into consideration in high-frequency equipment. At higher frequencies for example, the RF currents passing through the leads of the tube and into the tube capacitances encounter significant losses.



The Plate Tank Circuit of the Frequency Doubler is Tuned to a Frequency Twice That of the Input.

Another source of high-frequency loss is in the inductance of the cathode lead, for the cathode circuit is also part of the output. Excess energy is taken on by the space current electrons within the tube, due to the rapidly varying grid voltage, and some of this excess shows up in a bombardment of the cathode and general tube structure. Dielectric losses in the insulating material of the tube envelope and in the socket itself account for additional losses. Because of these many losses, it is common for the preceding stage to furnish a total power several times greater than that which actually reaches the grid as useful energy.

Inductance in the cathode is common to both the input and output of the stage and thereby causes degeneration. Special tubes with separate leads to the cathode, one for the grid return and one for the plate return, minimize this effect.

Still another source of power loss at high frequencies is the coupling between the grid and plate circuits. There is also some loss through the interelectrode capacities within the tube. This allows degeneration by acting the same as a load on the output circuits, as if a resistor were placed in parallel with the plate tank. The over-all effect is to reduce the selectivity as well as the output voltage and power.

Triode tubes with their large grid-to-plate capacities are often useless at high frequencies because of losses and feed back. Before such tubes can be used as amplifiers they must be neutralized. Triode tubes may be used as frequency multipliers, but plate-to-grid feedback at the harmonic frequency is of such phase that it tends to reduce the harmonic content of the plate pulse and thereby lower the output.

Fortunately the amount of grid-to-plate capacitance in pentode tubes is very small and they require no neutralization for low-frequency and low-power stages.

Another advantage in using the pentode for frequency multiplication is the fact that its plate current is more independent of plate voltage. This allows a higher harmonic content in the plate current pulse without requiring an excessive grid bias, thus providing higher harmonic power at the output with less grid drive. Now that we have seen the various factors of frequency multiplication, let us study some typical circuits.

Buffer-Doubler

Figure 2 is the buffer-doubler stage of a typical Motorola transmitter designed to operate in the 144-172 mc range. The stage uses one half of a twin-triode type tube for economy of space and circuitry. (Where several multiplier stages are needed, one less tube socket is helpful in simplifying equipment design). Because of the low frequency and low power level at the buffer stage, the triode tube gives satisfactory service.

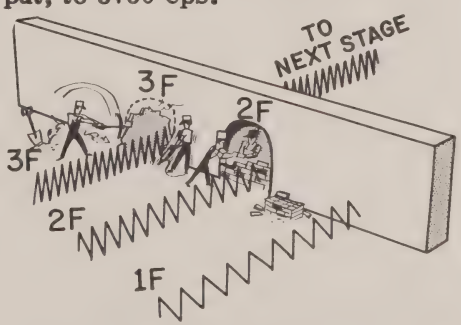
The stage following the oscillator or phase modulator is often called the buffer; it isolates the oscillator and modulator stages from the higher powered stages. The power dissipated in the grid circuit of the buffer is very small, and a fixed capacitor and resistor are used instead of the usual tuned circuit in order to maintain, as far as possible, a steady or constant impedance.

A small amount of grid-leak bias is provided and the operation is more likely to be in Class B2 than in Class C. (In Class B2, the bias is in the region of plate current cutoff and the grid, which is driven slightly positive, draws some current.) The harmonic content and the efficiency of the multiplier are sacrificed by this operation, but greater stability is obtained as a result.

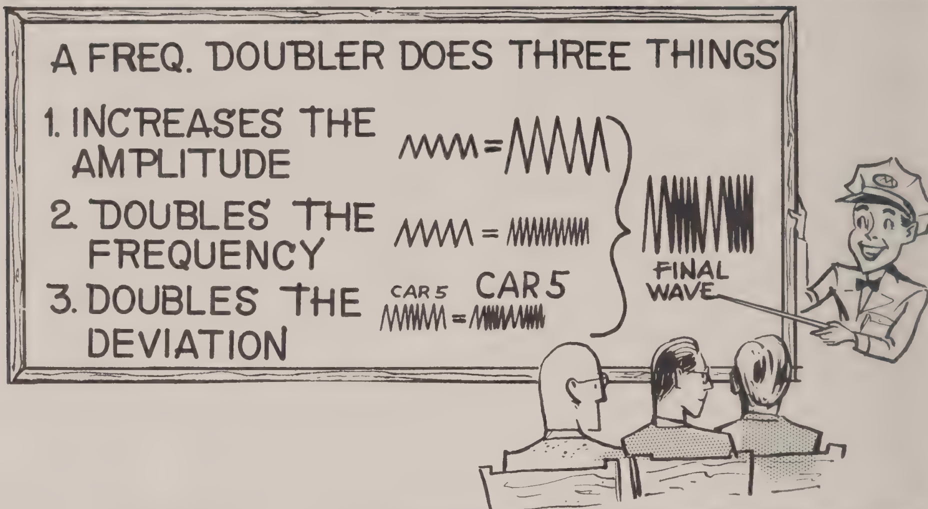
The plate circuit of the buffer-doubler is tuned to twice the input frequency. With a 7-mc oscillator, the input to the buffer is 7 mc and the output is 14 mc. A maximum deviation of 625 cps at the phase modulator is doubled to 1250 cycles. The output signal is transformer coupled to the grid of the following tripler stage.

Tripler Stage

The tripler stage of figure 3 operates with an input of 14 mc and a deviation of 1250 cps. The output of the stage is tuned to the third harmonic, or 42 mc. The deviation is also tripled in the output, to 3750 cps.



The Tripler Stage is Similar to the Doubler With the Exception That the Plate Tank is Tuned to the Third Harmonic of the Input Signal.



A Doubler Always "Doubles" the Frequency and the Deviation: the the Amount of Amplitude Increase Varies with Stage Design.

The stage uses a 6AU6 type tube, and for Class C operation the cathode is grounded and bias is provided by the grid-leak arrangement. The stage still operates at a relatively low power level and is not required to furnish much power to the grid of the following stage, the second doubler.

In order to provide for tuning the transformer between the first doubler and the tripler, a meter position is provided in the grid circuit. This meter indicates the relative amount of grid drive by indicating the grid current. Thus, both the primary and secondary of the transformer between the doubler and tripler are tuned for a maximum reading of this meter.

The plate tank of the tripler and the remainder of the stage do not have a capacitor placed in parallel with the plate coil. Tuning is provided by making the coil resonant with the capacitance of the circuit, including the coil capacitance, the capacitance of the wiring, etc. By using only the circuit capacitance in this manner, the inductance of the tuned circuit may be made larger than would be possible with a capacitor in parallel with the coil; this higher inductance provides a higher Q tank. In turn, this means a higher impedance, more voltage at the desired harmonic frequency, and good rejection of the other harmonics.

Second Doubler

The 42-mc signal from the tripler is doubled in this stage, which furnishes perhaps as much as one watt of power at 84 mc to the grid circuit of the doubler-driver. In addition, the deviation is doubled from 3,750 to 7,500 cps (7.5 kc).

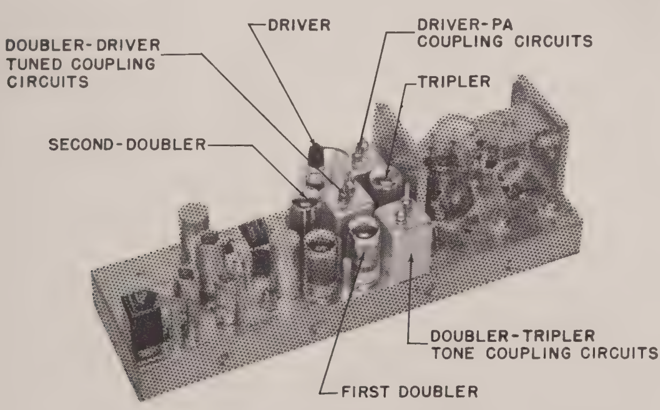
The 6AK6 tube is capable of supplying this required power, which is transferred by means of the double-tuned transformer. Except for the higher frequency and higher power considerations, the circuit is similar to the tripler. At higher frequencies the coil has fewer turns and greater care must be taken to minimize the capacitance of the circuit. The tube must have better high-frequency characteristics---less interelectrode capacitance, for example. With more power in the tuned circuits, there must be greater physical and electrical isolation between the input and output tanks.

Doubler-Driver

In this last multiplier we reach the operating frequency of 168 mc with a deviation of 15 kc. The tube must have good high-frequency characteristics and it must be capable of delivering from two to four watts of RF power at the channel frequency. The 2E26 type tube, designed for use in medium powered stages of a transmitter, meets these requirements for the frequency involved. A definite decrease in power would be noted, however, at higher frequencies.

Unless power stages of this type are protected by fixed bias, tube damage may result if the excitation should fail. Without excitation there is no grid bias, so the plate current would soon become excessive and damage the tube. Protection is provided the driver in figure 3 by returning the grid-leak resistor to a source of fixed negative bias, in this case about 20 volts. Should the exciting voltage from the preceding stage decrease or fail altogether, the fixed bias prevents the plate current from increasing beyond a safe level.

The amount of driving power provided by this stage may be several watts, the exact amount



This Photo of a Typical Motorola Transmitter Shows the Parts Location of the Multiplier Stages.

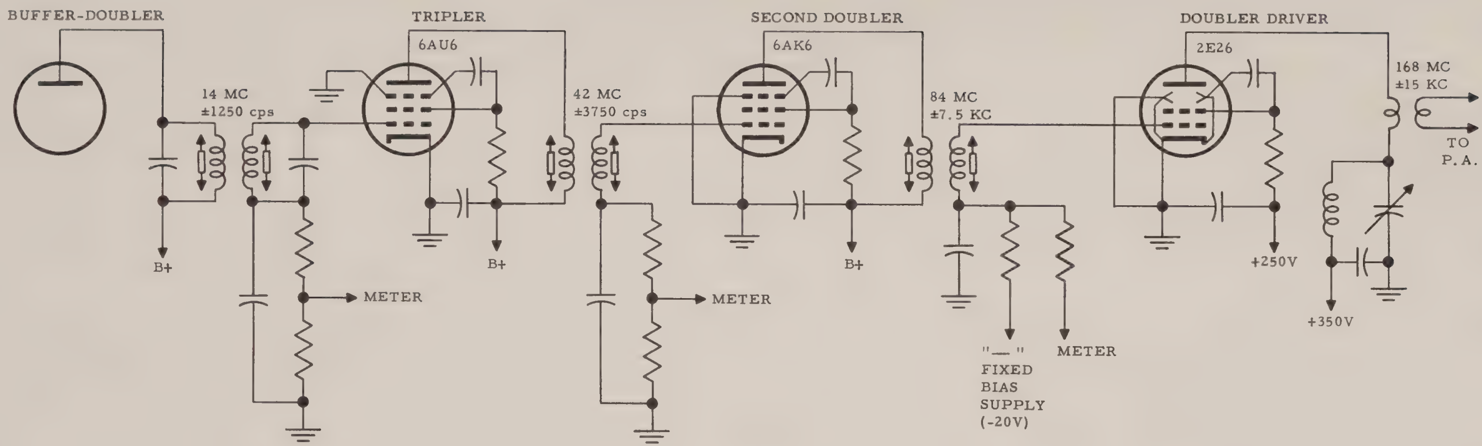
depending upon the output desired from the final stage.

If it should be necessary for the final amplifier to provide a greater output, the excitation from the driver must be higher. The power from the doubler-driver is controlled to a considerable degree by its plate and screen supply.

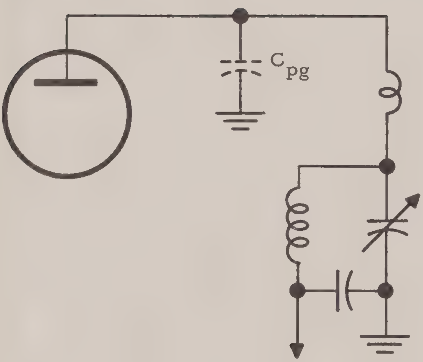
The tuning circuit for the plate tank is interesting. In figure 3 it appears that the coil is tuned by a series capacitor, but figure 4 better illustrates the electrical action of the plate tank circuit.

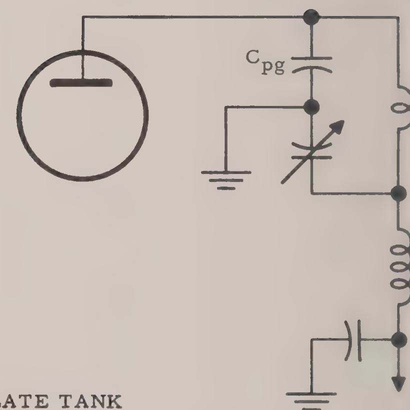
In 4A capacitor Cpg represents the total capacitance between the plate and ground. Figure 4A is redrawn in 4B for convenience of analysis---the circuit, however, is the same. Here it is seen that the plate-ground capacitance is actually in series with the tuning capacitor, therefore the total capacitance is less than Cpg alone. Furthermore, this total capacitance is in parallel with the coil and forms a conventional tank circuit arrangement. With this lower total capacitance, the tank inductance may be made greater, resulting in a higher tank impedance.

This completes our discussion of the transmitter with the exception of the power amplifier. The next lesson is devoted to this final stage of the transmitter.



TRANSMITTER
FREQUENCY MULTIPLIERS
FIGURE 3.





DOUBLER-DRIVER PLATE TANK

FIGURE 4A

FIGURE 4B

national

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The Power Amplifier

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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-6
FM TRANSMITTERS

The Power Amplifier

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
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PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

THE POWER AMPLIFIER

LESSON TA-6

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Whether the product removed from the earth is coal or uranium, you'll see two-way radio providing an assist. The nation's surface coal miners find radio a necessity for keeping their multi-million dollar investment in 24 hour a day operation.

THE
POWER AMPLIFIER
Lesson TA-6

General Considerations

The power amplifier raises the level of the RF power to the desired output of the transmitter. It is the last stage which the signal encounters on its way to the antenna and for this reason it is often called the final amplifier, or "final." It goes without saying that this final power stage should operate as efficiently as possible. This is particularly true in mobile applications where the primary power is limited to the battery and generator.

The efficiency of any device is the ratio of its useful output to its total input. In the power amplifier, it is the ratio of the amount of RF output (into the antenna circuit) to the DC power in the plate circuit. The output from the power amplifier is determined largely by (1) the type of tube employed, (2) the supply voltages, (3) the efficiency of its tank circuit and (4) the grid drive.

To produce a satisfactory amplifier output the preceding stage must furnish the required amount of grid drive.

Grid drive thus affects both input and output. Before considering this subject, however, it might be well to list the various requirements of the power amplifier stage.

Power Amplifier Requirements

1. General Adaptability. The tube and associated circuitry selected for the power amplifier stage must be capable of efficient operation at the transmitter frequency and all the components must be able to withstand the constant vibration and jarring to which they will be subjected in mobile applications.

2. Grid Drive and Bias. Assuming that sufficient grid driving power is available, grid bias must be high enough to establish Class C operation. Both fixed and grid-leak bias are commonly used in power amplifier stages.

Protective or fixed bias is necessary in order to prevent tube damage if the excitation should fail.

3. Plate Tank. The amount of RF power available depends upon the design of the plate tank.

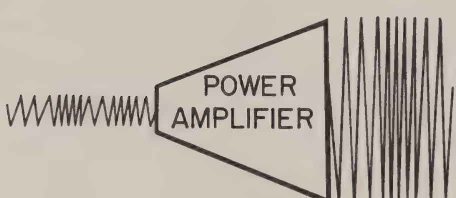
An impedance match to the antenna is essential for the efficient

transfer of power to the antenna system.

4. Tuning. The method of loading the antenna and the entire tuning procedure must be simple and reliable---lengthy tuning procedures involving erratic indications must be avoided.

5. Spurious Frequencies. All spurious frequencies, including unwanted harmonics and parasitics must be suppressed. Neutralization, filters, and other harmonic and parasitic suppressors are normally required in high-power, high-frequency stages.

The above requirements of the power amplifier stage will be discussed in connection with typical high and low-band Motorola transmitters operating at various power levels.[1] We shall begin with the subject of grid bias and grid driving power.



The Power Amplifier Increases the Power of the FM Wave Without Altering the Frequency or the Deviations.

Grid Drive and Grid Bias

Figure C is a partial schematic of the final amplifier stage to be found in a typical Motorola transmitter. The grid leak (R1 and C1) establishes Class C bias when sufficient excitation is applied to the grid. Grid-leak operation was described in connection with the limiter stage of the receiver and the operation of the circuit in the transmitter is basically the same. The amount of power dissipated in the limiter, however, is very small and can be disregarded, while in the case of the transmitter the grid is driven much harder and the grid current is considerably greater.

The amount of grid drive and grid impedance required for the particular tube being used can be determined by consulting published tube ratings. (Triodes, for example, generally require more drive than tetrodes or beam power tubes for the same power output.) For maximum power output with highest efficiency and minimum spurious emission, the correct grid impedance must be used. The recommended drive voltage, too, should be carefully observed in order to prolong the life of the tubes and secure optimum operation.

1. See TM 11-662, pages 178-181; also TM 11-668, pages 72-73.

Protective bias is established in figure 1 by returning the grid resistor (R1) to the negative terminal of a 20-volt fixed supply. This protective bias prevents the plate and screen currents from reaching dangerously high values at times of no grid excitation. This bias, however, has no appreciable effect on the Class C operation of the stage, which is established by the grid leak bias.

We next turn our attention to the matter of excitation (grid drive from the preceding stage). Without any excitation, the output of the power amplifier is zero. As excitation is applied and increased, the RF in the plate circuit also increases and this relationship continues up to the condition of nearly full power output. Once this point has been reached, additional grid drive will no longer add appreciably to the output.

Some extra drive is still desirable, however, in order to secure what is known as "stage reserve." Tube aging and other natural causes effectively reduce the excitation and this ordinarily reduces the transmitted power as well. With stage reserve, however, the transmitted power is maintained even after the original excitation has been reduced.

While reserve excitation is desirable, excessive excitation is equally undesirable.

Tetrodes and pentodes suffer from excessive grid dissipation if the excitation is too high. Moreover, these tubes show a decided increase of screen current when the grid drive is excessive. This results in a large drop across the screen resistor, a low screen voltage, and a decrease in plate power.

This Photo Shows the Driver and Final Amplifier Stages of a Modern Mobile Receiver.

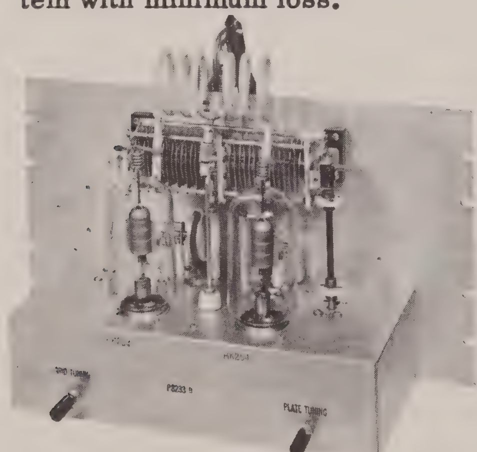
Grid bias is an important factor in the operation of the power amplifier stage. Too large a bias restricts the plate current to a very small portion of each input cycle. Although the efficiency may be improved as a result, less power is available in the plate circuit, for this power depends not only upon the supply voltage and the magnitude of the plate current pulse, but also on the duration of the pulse. Too little bias, on the other hand, means that the plate current exists for a considerable portion of each input cycle, and this reduces the efficiency of the stage.

The above discussion illustrates the importance of grid drive and grid bias in the power amplifier stage. The amount of grid drive or excitation and the value of the bias which is established by the

grid resistor directly affects the operation of the grid or input circuit.[2]

The Plate Tank

The plate tank circuit of the final amplifier is essentially the same as the plate tank circuit discussed in connection with the multiplier stages of the transmitter. The major difference has to do with power. The multiplier stage furnishes an appreciable amount of "driving" power to the grid of the following stage, but this is insignificant compared to the power handled in the final amplifier. This power, moreover, must be transferred to the antenna system with minimum loss.



Here we see a 250-Watt, Low-Band Final Amplifier.

The antenna system has a "loading" effect on the operating Q of the plate tank, much as if a resistor were placed in parallel with the coil. Because of the large power consumed by the antenna system, this reflected resistance is low in normal operation, and the Q of the coil will be correspondingly low. The operating Q thus depends on more than just the plate coil and capacitor. For the rejection of spurious emissions and for efficient operation generally, this loaded Q should be at least 10.[3]

The antenna load on the plate tank is determined by the coupling between the tank and the antenna system, and the optimum degree of coupling varies from one application to the other. In mobile installations, for example, where primary power is at a premium, a maximum proportion of the available power must be transferred to the antenna---the coupling must be close. This tends, of course, to increase the harmonic and spurious emission, but it is still advisable in such cases to secure as much radiated power as possible. The unwanted emissions can then be minimized, in most installations, by inserting a harmonic filter between the plate tank and the antenna.

Such a filter is shown in figure 1, composed of a coil (L3) and two capacitors, one at each end of the coil. This arrangement is tuned to a frequency higher than the operating frequency of the transmitter. This low-pass filter is effective in suppressing the undesired energy, most of which has a higher frequency than that of the transmitter, with very little attenuation (insertion loss) of the energy at the operating frequency.

2. See TM 11-668, page 74 and pages 77-80.

3. See TM 11-668, pages 80-84.

Antenna Coupling Circuit

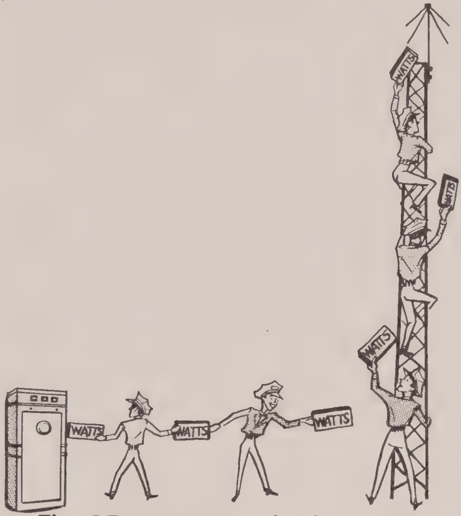
The RF power in the final amplifier of figure 1 is coupled to the antenna system by "transformer action." The plate tank coil acts like the primary of an RF transformer and the antenna is loaded by moving the secondary coil with respect to the primary, thus changing the mutual inductance. This is the reason that the inductance of the final amplifier tank coil is probably larger than would be expected--the higher inductance improves the over-all efficiency of the transformer.

Before it is coupled to the antenna, the plate tank is adjusted for resonance. This is accomplished by tuning the plate tank while observing the plate current meter. The tank offers maximum impedance to plate current at resonance, and the meter reading will be minimum at this point.

As the coupling is increased, a lower resistance is reflected in parallel with the plate tank, reducing both the Q and the impedance. This causes an increase in the plate current.

The coupling should never exceed the amount recommended by the manufacturer. Excessive coupling tends to increase the spurious output of the transmitter and the excessive plate dissipation may damage the output tube.

Most two-way mobile transmitters use tight coupling in order

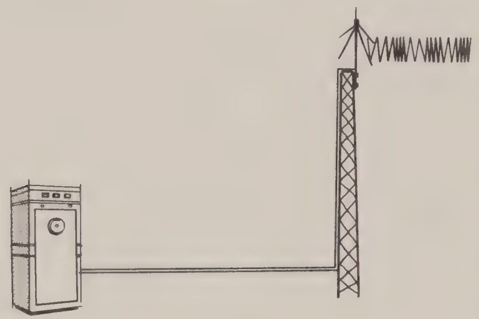


The RF Power Available at the Transmitter is of No Use unless it is Transferred to the Antenna and Radiates into Space.

to transfer the maximum power available to the antenna. When the antenna is fully loaded in this manner, a minimum plate current reading on the meter can no longer be relied on as a positive indication of resonance--the tuning is too broad. Thus, the plate tank should not be retuned unless some means is provided for monitoring the actual power output from the antenna; the plate tank may then be retuned, but only for maximum radiated power and not for minimum plate current.

In order to properly load the antenna, two conditions must exist: (1) the antenna must be resonant, and (2) there must be a reasonable impedance match between the antenna and the final amplifier. (An impedance ratio of 2:1 or less is considered "reasonable.") A nonresonant (or reactive) antenna will

reflect a reactive component into the final plate circuit, detuning that circuit and producing erratic plate-current readings when the antenna is loaded. An impedance mismatch has a similar effect. It is impossible for all the power available at the antenna to be dissipated or radiated when there is a serious mismatch, and much of this power returns to the final.



The Coaxial Transmission Line is the most Practical Method of Transferring the RF Power from the Two-Way Radio Transmitter to the Antenna.

The amount of impedance reflected from the antenna into the plate tank is also determined by the coupling, varying as much as 100 to 1 between conditions of minimum and maximum coupling. Maximum power is available only when the coupling is at an optimum setting; otherwise, the antenna will not provide the necessary load on the amplifier and the resulting mismatch reduces the efficiency of the system.[4]

Thus, maximum transfer of power to the antenna depends not only on the loaded Q of the plate tank, but to an equal extent on the impedance of the plate tank, transmission line and antenna. For the transfer of maximum power from a source of energy to its load, the impedance of the load must match the internal impedance of the source. Let us look further into this relationship between power transfer and impedance matching.

Power and Impedance Matching

Proof of the effect that impedance matching has on the amount of power delivered to the load can be seen in figure 2, where we have assumed that the impedance of the source is 10 ohms (represented by the external resistor), and the load resistance is varied between 1 ohm and 50 ohms.

The chart shows what happens when the load resistance is varied. The two resistances (load and source) are in series with each other, and the total resistance is their sum (shown in the second column of the chart). The current, which is the same in all parts of the circuit, is shown in the next column. The remaining columns show the calculated load voltage, load power, internal power and total power .

An impedance match takes place when the resistance of the load is the same as the 10-ohm resistance of the source. In the "load power" column we find that the maximum power (250 watts) is realized at this point. All other values of load resistance, whether above or below that of the source, result in a mismatch, and in each

4. See TM 11-668, pages 85-86.

case the load power is less than 250 watts.

With a load resistance of 1 ohm, the total resistance is low and the current is high. The total power is also high, but it is not evenly distributed between the load and source, most of it being wasted in the internal resistance of the source. This arrangement is obviously very inefficient.

As the load resistance is increased, the current decreases. The total power taken from the source is less and the arrangement becomes more efficient. As the load resistance approaches the value of the internal resistance of the source, the load power also increases. At the point of impedance match (10-ohm load), the load power is the maximum obtainable. The power dissipated in the load is now the same as the power dissipated internally at the source, and the efficiency has increased appreciably.

When the load resistance is increased beyond 10 ohms, the load voltage is also increased, but all other values--current, load power, internal power and total power--are decreased. Less power is now wasted in the internal resistance, and the efficiency has been improved. The load power, however, is somewhat less than maximum.

In this lesson we are interested primarily in the power amplifier, and the above examples apply particularly to the transfer of power. Where the load voltage is the only consideration, however, and the power (and distortion) can be overlooked, the load is always made much greater than the source impedance.

It will be noticed, for example, that higher values of load resistance produce larger values of voltage across the load. This increase in load voltage becomes most noticeable when the load resistance is many times greater than the internal resistance of the source.

When the load resistance is either one-half or twice that of the source, the load power will have dropped from 250 to 222 watts, which means that a 2-to-1 mismatch reduces the load power to 89 percent of maximum. If the load resistance is reduced one-fifth, to 2 ohms, the load power drops to 140 watts; if the load power resistance is increased five times, to 50 ohms, the load power again drops to 140 watts. Thus a mismatch of 5-to-1 reduces the load power to about 50 percent of maximum.

Resistors were used in the above examples, for simplicity of presentation, but the principles can be applied just as well to the antenna, which acts as a load on the power amplifier. Unless the antenna is absorbing and radiating all the RF power available from the amplifier, there will be an excess of RF in the final and the tube is likely to overheat. Maximum power is delivered to the antenna only when there is an

impedance match between the antenna system and the power amplifier. If the load maintains an impedance ratio of 2 to 1 or less, the load power will remain reasonably close to maximum. The load power will be considerably less, however, when the mismatch is greater than 2 to 1.

Three important conclusions can be drawn from the above discussion. (1) Maximum load power can be realized only when the impedance of the load is equal to the impedance of the source. (2) When the load resistance is high, with reference to the internal resistance of the source, the load voltage will be high. (3) If a mismatch is desired, greater efficiency is obtained by increasing the impedance of the load.

Spurious and Harmonic Emission

Spurious emissions and harmonics are unwanted signals generated within the transmitter and appearing in the output. They may be of any frequency other than the fundamental. Whole number multiples of the operating frequency are known as harmonics; all other unwanted outputs are spurious emissions.

When spurious emissions fall within the channel band they are transferred to the antenna along with the desired energy.

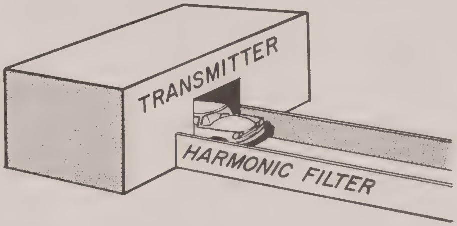
Spurious emissions are usually generated when unwanted harmonics of the multiplier stages combine with other frequencies that may be present to produce a signal within the pass-band of the final stage. Self-oscillation within any of the stages, particularly the final, is another source of spurious energy. These signals are avoided only by proper circuit design and parts placement, including adequate shielding. One of the most effective methods of minimizing spurious energy is to establish a low value of frequency multiplication between the oscillator and the final.

Harmonic radiation is generally regarded as the most objectionable form of unwanted emission. Because they are considerably higher in frequency than the fundamental, harmonics can be effectively removed from the output by the harmonic filter. This will eliminate the interference caused by harmonic radiation.

Thus it is not sufficient to merely introduce suppression at the transmitter output---the level of these unwanted signals must be minimized throughout the entire transmitter. This is partly determined by the interstage coupling, which is designed to provide the necessary drive to the following stage with sufficient reserve drive, at the same time holding the spurious and harmonic energy to a low value.

The importance of this interstage coupling cannot be overemphasized, especially in connection with service procedures. The coupling between the stages of the transmitter is a fixed quantity and

must never be changed by the serviceman. It is possible, for example, to increase the drive into the final stage by increasing the coupling from the preceding stage, but to do so will only increase the spurious and harmonic content along with the strength of the carrier. The output will contain an excess of off-channel energy---usually beyond the maximum allowed by the FCC. Normally, the only coupling which may be adjusted to provide the specified output is that between the final and the antenna. Even then, the recommended procedure must be followed in detail, particularly the part about increasing the coupling beyond the critical point determined by plate current.



Undesired Signals are Rejected by the Harmonic Filter at the Transmitter Output.

Feedback and Neutralization

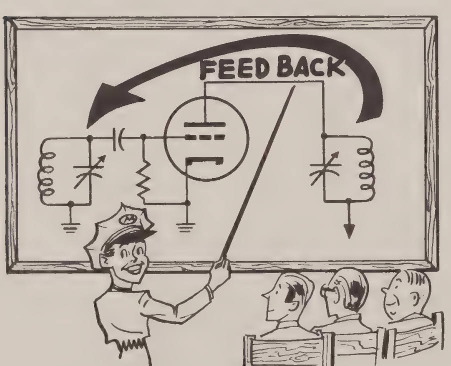
Feedback in a power amplifier is the returning of a portion of the output energy from the plate circuit to the grid or input circuit. If the energy is fed back in phase with the signal voltage acting on the grid, the feedback is said to be positive, or regenerative. If this feedback voltage is 180 degrees out of phase with the grid signal, however, the feedback is called negative, or degenerative.

Degenerative feedback reduces the amplification of the stage, because the feedback voltage opposes the original signal voltage. Regenerative feedback, on the other hand, effectively increases the amplification, because the feedback voltage adds to the original signal voltage and the resulting larger voltage on the grid causes a larger output voltage.

The immediate effect of regenerative feedback is to strengthen the signal, but this means more RF in the plate circuit which, in turn, means still more feedback to the grid. The cycle continues in this manner until the stage breaks into a self-sustained oscillation. The oscillation is often at a frequency within the transmission band of the transmitter and reaches the antenna along with the desirable carrier, now considerably weakened.

Where the amplifier stage is operating at a low power level and at a low frequency, the feedback is not so noticeable and can often be disregarded. In the final stage of the transmitter, however, where the power is appreciable and the frequency is also often very high, feedback becomes a problem. Thus, in order to provide a stable power amplifier, it is obvious that something must be done about this regeneration.

Regenerative feedback may take place through the plate-grid interelectrode capacitance at the tube. Thus, the triode tube, with its relatively high grid-plate capacitance, is more subject to regeneration than tetrodes and beam power tubes. The inductance of the tube electrodes and their lead wires also is a source of feedback voltage, however, and the low regeneration of tetrodes and pentodes largely depends upon the screen grid remaining at ground RF potential. Where this is not possible the tetrode also becomes unstable, particularly at high frequencies.



Regenerative Feedback in an Amplifier Stage Causes Instability and may Lead to Oscillation.

At high frequencies, such as those encountered in the final stage of the high-band transmitter, the bypass capacitor for the screen grid does not always maintain the screen at ground RF potential, due to the inductive reactance of the lead wire from the screen element to the external connection. This otherwise small inductance has considerable reactance at high frequencies, and the screen is no longer grounded. As a result, the feedback energy increases and the stage becomes unstable.

While it is not possible to eliminate feedback, it is possible to "neutralize" its effects. This is accomplished by introducing a second feedback voltage which is out of phase with the other. This out-of-phase feedback counteracts the regenerative energy in the grid circuit and restores stability to the stage. This procedure of introducing an out-of-phase voltage which offsets the undesirable regeneration is known as "neutralization."

Triodes, because of their high interelectrode capacitance, usually require neutralization even at low frequencies, where tetrode and beam power tubes do not. While it is seldom necessary to neutralize the tetrode at the lower frequencies and at low power levels, these tubes often require neutralization at the higher frequencies.[5]

Our discussion has been limited, so far, to feedback due to either (1) the grid-plate interelectrode capacitance within the tube, or (2) the inductance of the screen grid lead. (Other sources of feedback are present, but these two are the most pronounced.) In neutralizing the amplifier, any feedback voltage due to either of these two factors must be counteracted. Other feedback energy can gen-

5. See TM 11-668, pages 86-88.

erally be reduced to an unimportant level by careful design, parts placement and shielding.

Neutralizing Circuits

A neutralizing circuit is one that nullifies the regenerative feed back through the grid-plate tube capacitance, by introducing another voltage of opposite phase. A typical neutralizing circuit is illustrated in the triode amplifier stage of figure 3. Considerable regenerative energy is fed back from the plate circuit to the grid through the interelectrode capacitance of the tube, and unless this energy is counteracted or neutralized, the stage will probably oscillate.

By grounding the center-tap between the two series capacitors connected across the coil, a push-pull arrangement is established in the grid circuit and the ends of the coil are of opposite polarity with respect to ground.

This arrangement is sometimes referred to as "grid neutralization." This form of neutralization is very popular, especially in single-ended stages, because the power level is comparatively low in the grid circuit, making it very convenient to establish the necessary push-pull voltages at the grid tank.

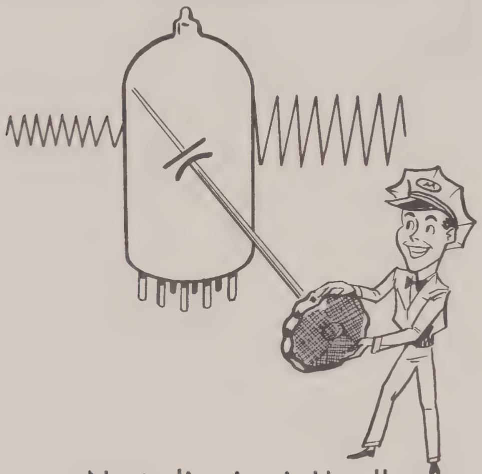
There are now two RF paths from the plate circuit to the grid circuit, one through the tube plate-grid capacitance and the other through the neutralizing capacitor, Cn. The value of this neutralizing capacitor is usually of the same order as the interelectrode capacitance.

Energy from the plate circuit is fed back through the plate-grid tube capacitance to the grid tank, where it tends to set up a circulating current. At the same time, plate-circuit energy is also fed back to the opposite end of the grid tank through the neutralizing capacitor, and this current also tends to set up a circulating current in the grid tank. These two currents, however, are 180° out of phase and oppose each other. Now, if the neutralizing capacitor is adjusted so that the two currents are of equal magnitude, they will cancel each other and the net current due to feedback from the plate to the grid will be zero.

The term "neutralizing," in connection with service procedures, refer to the actual adjustment of the neutralizing capacitor as described above, so that the circuit is properly balanced. Some circuits have fixed values for the neutralizing parameters and no such adjustments are required on the part of the serviceman. Whenever neutralizing adjustments are to be made, however, the serviceman should always follow the exact procedure specified by the manufacturer.

When a final amplifier is not properly neutralized, the tuning

will be erratic and the condition can be detected by observing the grid and plate currents on a meter as the grid and plate tanks are tuned through resonance. This becomes important when the stage is being neutralized. The actual procedure is as follows:



Neutralization is Usually Accomplished by Introducing a Second Feedback Voltage which "Neutralizes" the Regeneration.

First, disengage the plate supply and decouple the antenna from the stage being neutralized. The filament voltage is left on and the drive from the preceding stage must be normal. With no plate voltage to cause normal conduction in the tube, there will be no RF in the plate circuit other than that which is due to capacitive coupling from the grid. If the stage is neutralized, the RF feedback through the tube capacitance will have been exactly canceled by the RF introduced through the neutralizing circuit, and there will be no indication of RF in the plate tank. A low-voltage, low-current flashlight bulb (soldered to the ends of a single loop of wire and coupled to the plate tank coil) makes a good RF indicator.

The neutralizing capacitor is first set at minimum capacity (plates open). For this check the plate tank must be tuned to resonance. And, with the lamp properly coupled, the plate tank must be adjusted for a maximum indication on the lamp. The neutralizing capacitance is now gradually increased until the lamp goes out. (This will be the point of zero RF.) On either side of this setting, the RF in the tank should gradually increase in intensity and the lamp will light.

The final amplifier can also be neutralized by observing the grid current meter. The antenna is decoupled, as before, and the plate and screen supply removed. When the plate tank is tuned through resonance, there will be no change in the grid-current reading if the stage is neutralized. If the grid current should decrease slightly at this point, the stage is not completely neutralized. The decrease in grid current takes place because some of it is being absorbed by the resonant plate tank. When the plate circuit is not resonant, little or no energy is taken by the plate tank and the grid current is maximum.

The importance of neutralization---especially in the case of higher powered transmitters such

as the 250-watt base station---cannot be overemphasized, and it is particularly essential for full power output at the channel frequency. The spurious and harmonic content must be held to a minimum. It is also important in the case of the low powered transmitter, of course, but the adjustments here are usually less critical.

Low-power stages, in fact, can often be provided with neutralizing circuits of fixed values which will prove satisfactory for the entire operating range of the transmitter. Such a circuit is shown in figure 4-A, where the neutralizing capacitor, Cn, is not variable. The system itself is somewhat different from that of figure 3.

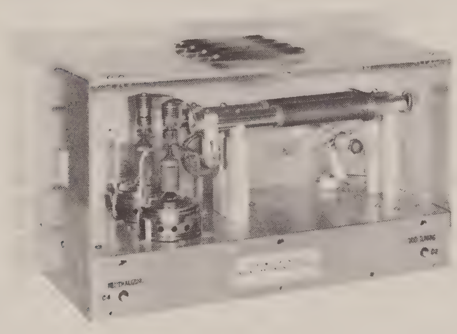
Neutralization is obtained by means of a balanced capacitance bridge, made up of four capacitors: (1) the neutralizing capacitor, Cn, (2) the fixed capacitor, C, (3) the grid-plate capacitance, Cgp, and (4) the grid-cathode capacitance, Cgk. The last two are not found as separate components on the schematic, but their position and relationship can be seen in figure 4-B, which has been redrawn to show the bridge arrangement.

The plate and ground are connected to two terminals of the bridge (P and K), while the grid tank is connected between the other bridge terminals (A and G). With the proper ratios existing between the four capacitors, the bridge will be balanced; any voltage between the plate and ground will be canceled in the bridge and there is no voltage applied to the grid tank. Thus there can be no feedback between plate and grid tanks when the bridge is balanced. While perfect neutralization at all frequencies may not be possible by this method, the remaining feedback will be negligible and the balance will be sufficient for normal transmitter operation.

The neutralizing circuit shown in figure 5-A applies only to tetrodes and beam power tubes. A common bypass capacitor, Cs, is employed for the screen and the bottom of the plate tank. This capacitor forms one leg of a balanced capacitance bridge, as in figure 4, but different capacitances are used for the other legs. The plate-ground capacitance, Cp, the plate-grid capacitance, Cpg, and the grid-screen capacitance, Cgs, are shown as separate components, for these are actually the total capacitances between the tube elements, whether external or internal to the tube.

As before, the circuit has been redrawn (figure 5-B) to show the bridge arrangement more clearly and for easier analysis. If the bridge of figure 5-B is balanced, it will be impossible for any voltage existing across the upper and lower bridge terminals (which is the voltage across the plate tank) to produce a voltage across the opposite terminals of the bridge (which in this case is across the grid tank). In this circuit, the screen and the bottom of the plate

tank must be above ground, as provided by the reactance of the screen bypass capacitor. To prevent the supply line bypass capacitors from placing this circuit at ground potential, a coil (L) is placed in series with the supply line, as shown.



A 250-Watt, High-Band Final Amplifier.

Neutralization At The Higher Frequencies

While the neutralization methods so far described apply to VHF and UHF as well as to the lower frequency ranges, several tube constants which are not particularly bothersome at lower frequencies must be taken into consideration in connection with the higher frequencies. Most important of these are the plate-screen capacitance, the screen-grid capacitance and the inductance of the screen lead. They are shown in figures 6-A and 6-B as external to the tube, for the purpose of this lesson, although they are actually inside the tube.

One of these---the screen inductance--is entirely negligible at the lower frequencies, but at higher frequencies it actually becomes a source of feedback, sometimes to such an extent that the tube becomes "self-neutralizing." In any case, the presence of this constant makes the task of neutralizing the stage easier, and it must be given full consideration at the higher frequencies.

The RF voltage at the plate produces a current through the plate-screen capacitance, Cps, and through the screen inductance, L, developing a voltage across the screen inductance 180 degrees out of phase with the RF voltage at the plate. (To indicate this out-of-phase condition, the voltage across the inductance, L, is designated as -E.) It should be noted here that all the circuit components of figure 6-A are pure reactances, so that they are always either in phase or 180 degrees out of phase. These components are rearranged in figure 6-B to show the voltages with respect to the grounded cathode, which will be considered as being at zero RF potential. Thus, while the plate is shown as being "above" the cathode (positive), the screen must be shown "below" the cathode, for the screen voltage due to the screen inductance is 180 degrees out of phase with the RF plate voltage.

If the stage is to be neutralized, the grid must be at ground RF potential with respect to feedback voltages, and it is thus shown in figure 6-B.

The RF plate voltage, being positive with respect to ground, is indicated by the vertical line, Ep. The RF screen voltage, developed across the inductance of the screen lead, is negative with respect to ground and it is indicated by the vertical line -E, below the level of the cathode (between screen and ground). The interelectrode capacitances between the grid and plate, Cgp, and between the grid and screen, Cgs, form a voltage divider between the plate and screen with the grid connected at their junction. The exact RF potential of the grid depends not only on the RF voltages of the plate and screen, respectively, but also upon the ratio of these interelectrode capacitances.

Now the reactances associated with Cgp and Cgs maintain a constant ratio for all frequencies, so the grid remains in the same relative position between the plate and screen. The RF voltages at the plate and screen, however, change in relative amplitude as the frequency changes. Thus, for a given tube there is always one frequency at which the tube will be self-neutralized.

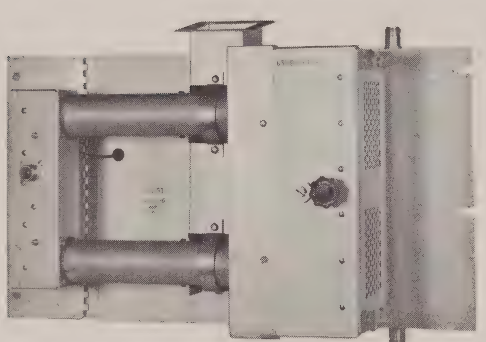
At any other frequency, the same tube may require neutralization. The reason for this is that the screen voltage increases and decreases as a function of frequency; when the frequency is increased the screen voltage rises, and when the frequency decreases the screen voltage drops. At frequencies lower than the self-neutralizing frequency, the screen voltage is too low and the grid is at a positive potential, which means that the tube has regenerative feedback. Likewise, when the frequency is higher than the self-neutralizing frequency, the screen voltage is too high and the grid is at a negative potential with respect to the cathode, which means that the tube has degenerative feedback.

This relationship between the screen voltage and the frequency is made use of when it is desired to neutralize the tube at other frequencies. At lower frequencies, the voltage would ordinarily be too low to neutralize the tube, so a small coil is placed in series with the screen to increase the voltage, making neutralization possible. If the added inductance is made larger than needed for the purpose, a small variable capacitor can be placed between the screen and cathode to effectively reduce the total inductance, thus making it possible to neutralize the tube over a wide range of frequencies. This arrangement is used in practical circuits. For higher frequencies, a screen bypass capacitor counteracts a portion of the excessive screen voltage, to bring the tube into neutralization.

25-Watt, High-Band Final

By taking the basic amplifier circuit of figure 1 and adding a few additional components, we will have the complete power amplifier circuit shown in figure 7-A,

which represents the final amplifier stage of a typical Motorola transmitter. The input to the stage comes from the preceding driver stage and the output is fed to the antenna system, as shown. The operating frequency is in the 144-174 mc band and the output is 25 watts.



A 250 Watt, 450-MC Final Amplifier.

Three power supply voltages are required---a high B-plus for the plate, a lower B-plus for the screen, and a negative protective bias for the grid circuit. Provision is made for lowering the voltage during the tuning operation by means of the HI-LO switch across R-3 in the screen circuit. When the switch is set at HI, it shorts out R-3 and the full screen voltage is applied. With the switch at LO, however, it is open, and the resistor is in the circuit. The extra voltage drop developed across R-3 lowers the screen voltage, which in turn lowers the plate current to a safe value for tuning.

A fixed bias of 20 volts is applied to the grid from the bias supply through R1. Class C bias and operation is provided by the signal applied to the grid from the driver stage. RF energy is prevented from entering the plate supply by means of the coil L2 and bypass capacitor C3. The stage is neutralized throughout the operating range of the transmitter, as a result of the fixed voltage established at the screen and across L-1, which is sufficient to maintain the grid at the same RF potential as the cathode. The interelectrode capacitances of the tube and the capacitor, C1, are a part of this neutralizing circuit, and the neutralizing is accomplished in the same manner as in figure 6.

A resistor and capacitor in the grid circuit provide the means for metering the grid current. In the plate circuit, the meter is connected across the shunt in the plate supply line. When the plate tank is tuned to the same frequency as the signal impressed upon the grid, the plate current is minimum and this will be noted on the plate current meter. By using a meter of known sensitivity in connection with a shunt resistor of predetermined value, the exact amount of plate current can be determined. The power input, W, will be equal to the product of E times I, where E is the plate supply voltage and I is the plate current.

The final amplifier is coupled to the antenna through the RF

transformer, the antenna circuit being tuned by the capacitor in series with the secondary winding of the transformer. In order to properly load the antenna, all reactance must be tuned out. Since the reactance of the antenna will vary from one installation to the next, some means must be provided to tune out or cancel any reactive component in the antenna system. This is done by adjusting the trimmer in the antenna circuit.

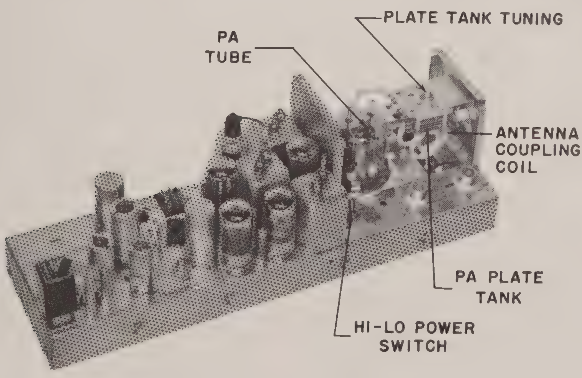
The antenna system includes the pi-type harmonic filter, composed of L3 and the two capacitors, and the transmission line and the antenna itself. The resistor R4 maintains the antenna system at ground potential as far as DC is concerned, and prevents high voltages from accumulating on the antenna.

The tuning capacitors in the grid and plate circuits appear to be in series with their respective tank coils, but when the electrical circuit is considered in connection with the interelectrode capacitances of the tube, it will be seen that both circuits are parallel tuned, in the conventional manner. The analysis is similar to that of the plate circuit in the driver stage previously discussed, and the circuit has been redrawn in figure 7B to show this relationship more clearly.

60-Watt, Low-Band Final

When a power output is desired which is much greater than the 25 watts obtainable with the amplifier of figure 7, the plate supply must be correspondingly larger. Then, in order to handle this greater power, the amplifier tube must have a higher power rating ---otherwise, two tubes must be used, connected either in parallel or in push-pull.

By using a dual tube such as the 829B, the advantage of two-tube



Here We See the Location of the Final Amplifier Stage Components in a Typical Two-Way Transmitter.

operation can be secured without sacrificing the simplified circuitry and compactness of a single tube. This tube contains two power tetrodes in a single envelope and they may be operated either in parallel or in push-pull. The parallel arrangement is simpler than push-pull and it is employed in the circuit of figure 8, which shows the final amplifier of a Motorola 60-watt transmitter operating in the 24-54 mc. range.

When tubes are operated in parallel, all the similar elements are connected together. In figure 8A, the cathode, suppressor grid and screen grid are common to both sections; the plates and grids are also regarded as parallel connected, despite the presence of parasitic suppressor resistors in the plate and grid leads. Parasitic suppressors are usually necessary in both the grid and plate leads of high-power stages, particularly where two tubes are used. Parasitic suppressors consist of resistors on which a small coil has been constructed, the ends of the coil being terminated at the ends of the resistors. One of these is located in each grid and plate lead to prevent parasitic oscillations from being established; they prevent the grid and plate from forming high-frequency tuned circuits and producing a parasitic signal which would be radiated from the antenna. In each case, these parasitic suppressors are located close to the terminals of the tube.

The output circuit is the same as that of figure 7 and it is omitted from figure 8A. A protective bias of approximately 20 volts is provided, also similar to the arrangement in figure 7, and the metering is performed in the same manner as discussed for figure 7. The coil in the plate supply prevents RF from entering the supply line, and a series resistor is used as a meter shunt.

The plate tank is tuned by the variable capacitor in parallel with the tank coil. Due to the reactance of C3, which is in series with the tuning capacitor, the bottom of the coil is not at ground potential. The HI-LO switch in the screen circuit is used to lower the screen voltage and plate current when the transmitter is being adjusted.

The screen does not form any part of the neutralizing circuit. The RF voltage at the top of the tank, which is fed back to the grids through the interelectrode capacitance of the tube, is neutralized by the out-of-phase voltage at the bottom of the tank, fed back to the grids through C1, C2, and C4. The neutralizing circuit has been redrawn in figure 8B to illustrate this action.

60-Watt High-Band; Push-Pull Operation

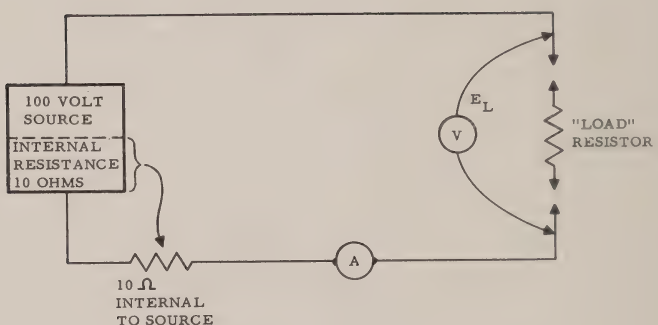
Figure 9 shows the final stage of a Motorola 60-watt transmitter,

operating in the 144-174 mc band. This stage also uses two sections of an 829B (since the power output is the same as for the 24-54 mc transmitter just discussed) but the circuitry is considerably different because of the higher frequencies involved. When tube elements are connected in parallel as in figure 8, the interelectrode capacitances are increased. These capacitances are tolerable at low frequencies, but they cause greater feedback and lower efficiency as the operating frequency is increased. Thus in the high-band transmitter, a push-pull arrangement must be used.

When tubes are operated in push-pull, the grids and plates of the two tubes are connected to opposite ends of a balanced circuit, as shown in figure 9. At any instant, the ends of the secondary winding of the input transformer will be at opposite polarity with respect to the cathode (ground) connection, so the grid of one tube is swung positive at the same instant that the grid of the other is swung negative. Hence the voltages and currents of one tube are out of phase with those of the other tube. The plate tank is also connected in push-pull, with the B supply fed to the center of the tuning coil, but the "coil" in this case consists of a tuned line, which is most efficient at these high frequencies. Tuning is accomplished by means of a slider located between the two plate lines. The slider changes the electrical length of the plate "coils," and hence the inductance.

Neutralization is usually a simple matter in a push-pull amplifier. The conventional method is to connect the two plates to the opposite grids through small neutralizing capacitors. (This arrangement is sometimes referred to as "cross neutralization.")

Two RF paths are thus provided to the grid of each tube. One of these paths is between the plate and grid of the same tube through the interelectrode capacitance; the other path is between the plate of one tube and the grid of the other tube, through the neutralizing capacitor. The voltage fed back through one path is 180 degrees out of phase with the voltage fed back through the other path, since the plates are operated in push-pull. With the proper degree of coupling, the two RF voltages will cancel each other in the plate circuits, and the total effective feedback is zero.

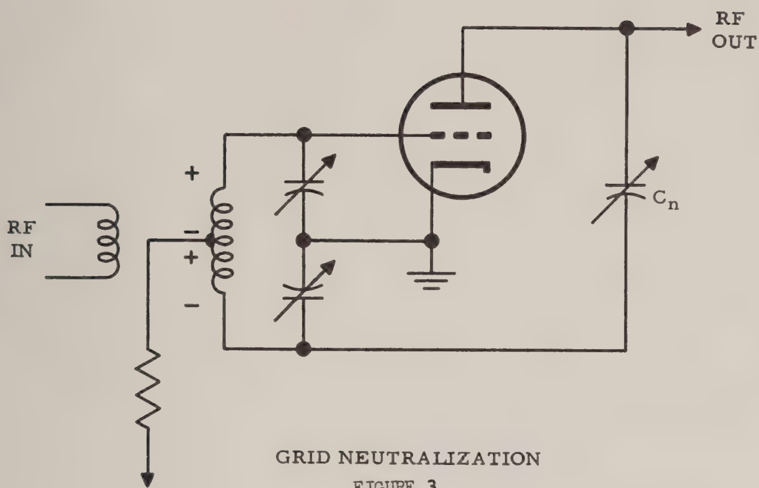


$R_{TOTAL} = R_{LOAD} + R_{INTERNAL}$
CURRENT (I) = E/R
LOAD VOLTAGE (E_L) = I x R_{LOAD}
POWER (WATTS) = I^2 R, E x I , or $E^2 \div R$

LOAD RESISTANCE	INTERNAL RESISTANCE	TOTAL RESISTANCE	CURRENT	LOAD VOLTAGE	LOAD POWER	INTER. POWER	TOTAL POWER
1 OHM	10 OHMS	11 OHMS	9.1 AMPS	9.1 VOLTS	83 W.	830 W.	913 W.
2 "	10 "	12 "	8.33 "	17 "	140 "	700 "	840 "
5 "	10 "	15 "	6.67 "	33 "	222 "	444 "	666 "
10 "	10 "	20 "	5.0 "	50 "	250 "	250 "	500 "
15 "	10 "	25 "	4.0 "	60 "	240 "	160 "	400 "
20 "	10 "	30 "	3.33 "	67 "	222 "	111 "	333 "
50 "	10 "	60 "	1.67 "	83 "	140 "	28 "	168 "

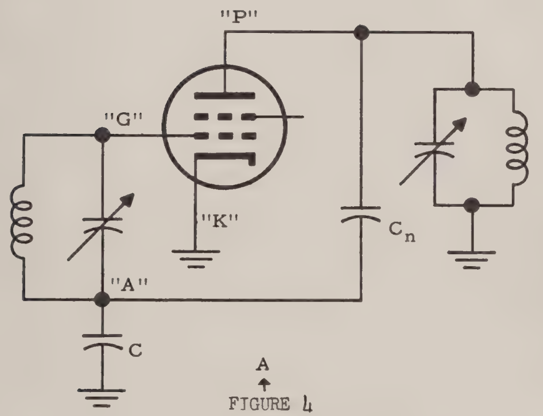
IMPEDANCE MATCHING AND LOAD POWER

FIGURE 2



GRID NEUTRALIZATION

FIGURE 3



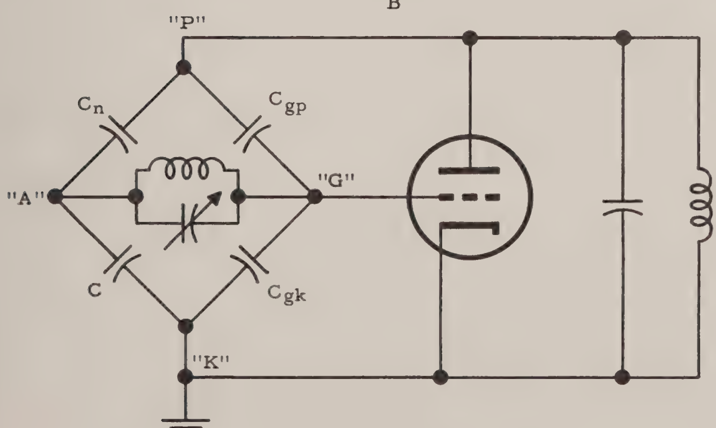
A

↑

FIGURE 4

↓

B



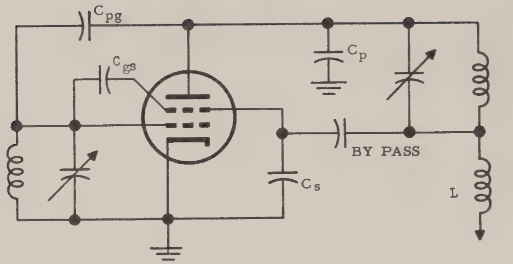


FIGURE 5A

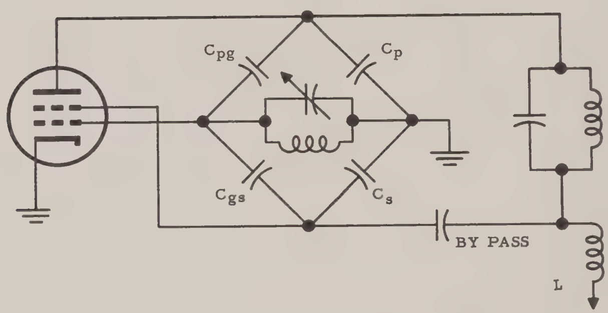


FIGURE 5B

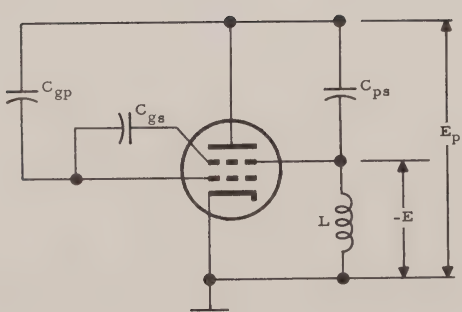


FIGURE 6A

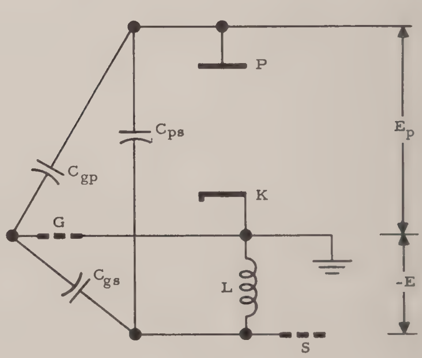


FIGURE 6B

STUDENT NOTES

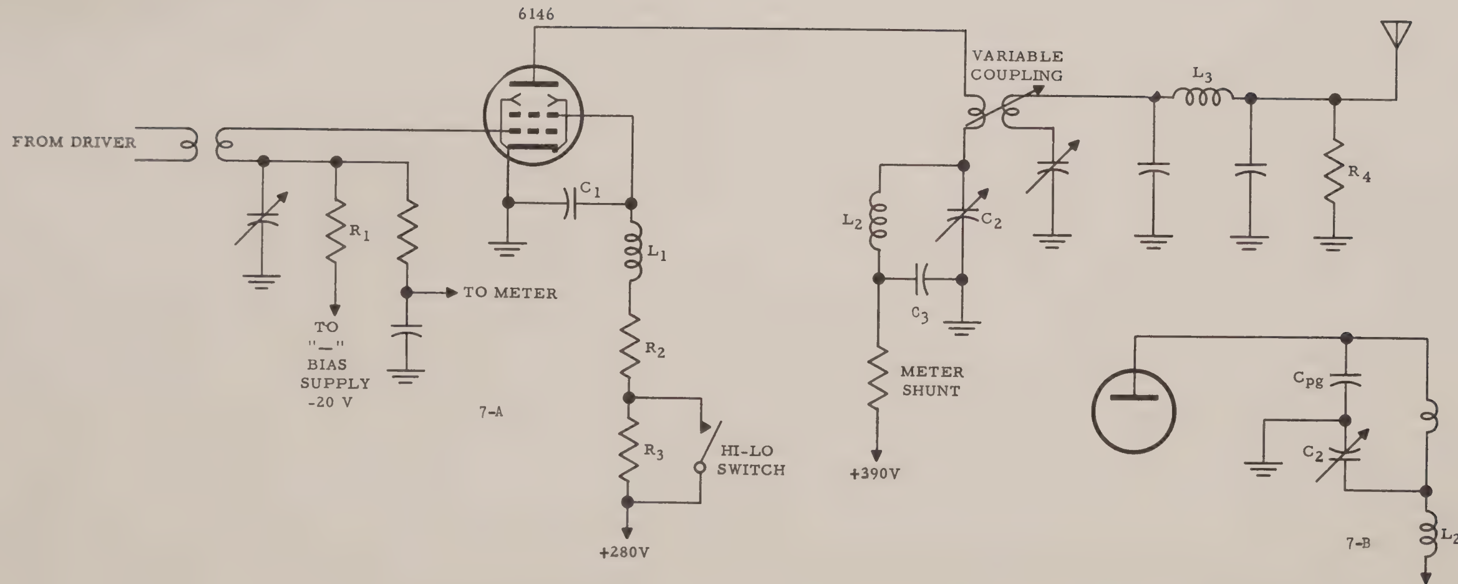
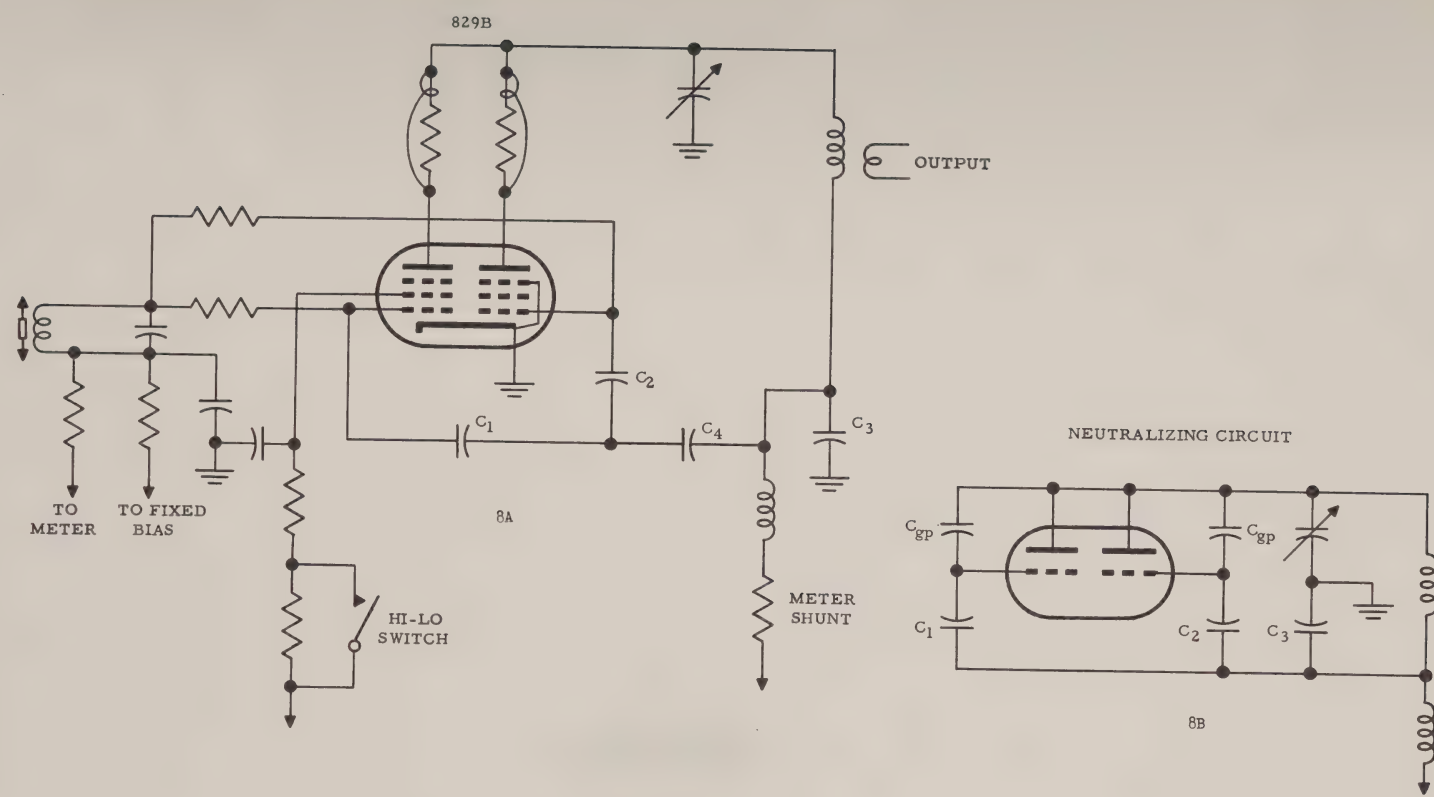
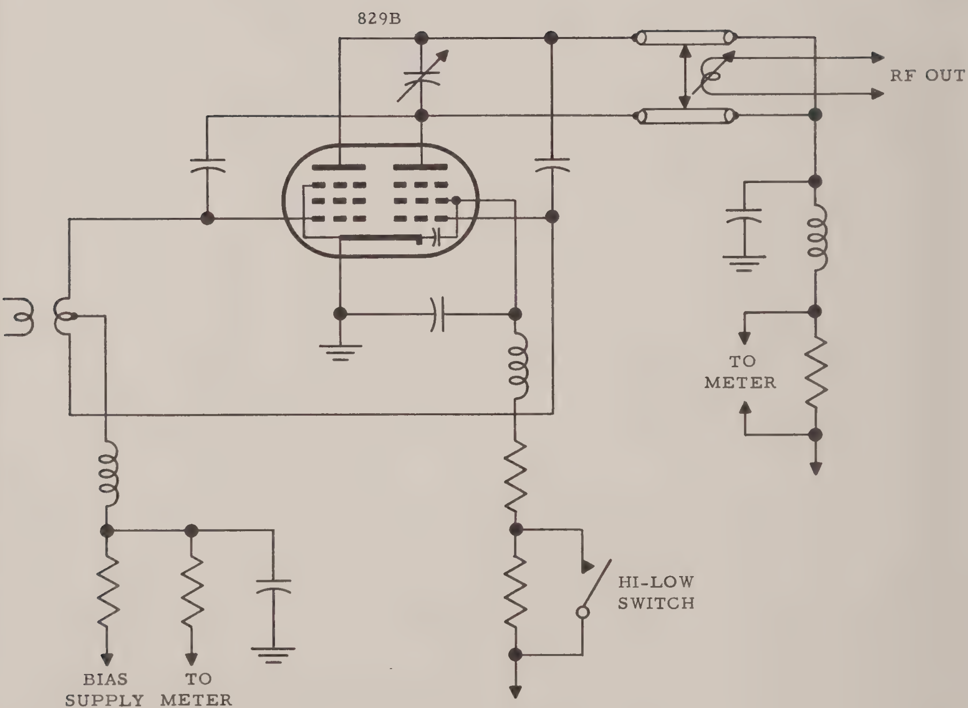

6146
FROM DRIVER
R1
TO METER
TO
"–"
BIAS
SUPPLY
-20 V
C1
L1
R2
R3
HI-LO
SWITCH
+280V
7-A
VARIABLE
COUPLING
L3
R4
L2
C2
C3
METER
SHUNT
+390V
Cpg
C2
L2
7-B

FIGURE 7



PARALLEL OUTPUT 30-50 MC
FIGURE 8



PUSH-PULL OUTPUT, 150-170 MC

FIGURE 9

national

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RADIO COMMUNICATIONS

service

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-7
FM TRANSMITTERS

The Meter in the Transmitter

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-7
FM TRANSMITTERS

The Meter in the Transmitter

—one of a series of lessons on two-way FM communications—

MOTOROLA **TRAINING INSTITUTE**
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PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

THE METER IN THE TRANSMITTER

LESSON TA-7

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Busy executives--in industry, or in this case, of an art institute--have enthusiastically accepted "radio paging." System provides selective, private voice paging of personnel anywhere in building.

THE METER IN THE TRANSMITTER

Lesson TA-7

Introduction

Rapid, accurate alignment and servicing of a transmitter can be accomplished only if some convenient means is provided for giving an indication of the performance of each stage in the unit. In Motorola communications transmitters, the metering system is the same as that already described for the receiver, and the same test set can be used. The transmitter metering circuits include the necessary components to permit the use of an ordinary 50 microampere meter for checking the voltages at the metering points.

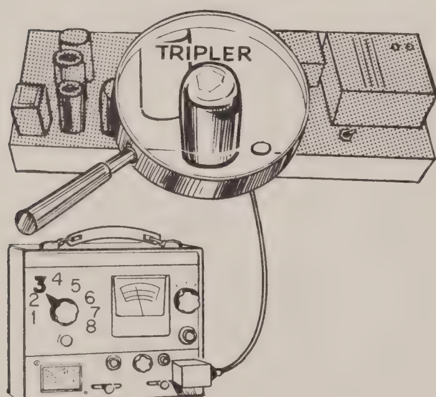
The Metering System

The transmitter metering can best be explained by means of a block diagram. Figure 1 shows the location of the metering points in a typical Motorola high-band transmitter. The encircled numbers indicate the points on the metering socket to which the leads are connected and correspond to the positions on the switch of the test set. The PA plate current is measured between pins 7 and 8 of the metering socket; these two pins are at a high DC potential with respect to ground, pin 11.[1]

The Important Circuits of Motorola Transmitters may be Measured by Plugging-In a Motorola Test Set and Turning a Selector Switch.

1. Latter lesson give details about the Motorola Test Sets and their use in aligning and servicing the transmitter.

Before beginning any service procedure on the transmitter, the serviceman should place the HI-LO switch in the LO position. (This switch is on the transmitter chassis in some models; in other models, it is on the power supply chassis.) In the LO position, the screen voltage of the final stage is reduced to a low value to prevent excessive plate current. Only after the proper amount of grid drive at the final is established and after the final plate tank is tuned to resonance should this switch be returned to HI.



In Switch Position 3, the Motorola Test Set Indicates the RF Level at the Grid of the Tripler Stage.

Tripler Grid--Meter Position 3

When the meter is switched to position 3, it indicates the level of the RF applied to the grid of the tripler stage. The meter thus serves as an RF output indicator for the oscillator, phase modulator, and buffer-doubler stages.

In the block diagram of figure 1 we find two arrows between the buffer-doubler stage and the tripler stage. These arrows indicate the primary and secondary, respectively, of the interstage coupling transformer (the plate tank and the grid tank). When either the primary or the secondary of the transformer is adjusted to resonance there should be a clearly defined peak indication on the meter. Failure to establish such a peak means that something is not operating as it should. The adjustment of these circuits to resonance produces maximum RF at the tripler grid. This will be indicated by a maximum reading on the meter.

When the reading of position 3 is close to the value recommended by the manufacturer for the particular transmitter, we can be reasonably sure that the three preceding stages as well as the grid of the tripler are all operating normally.

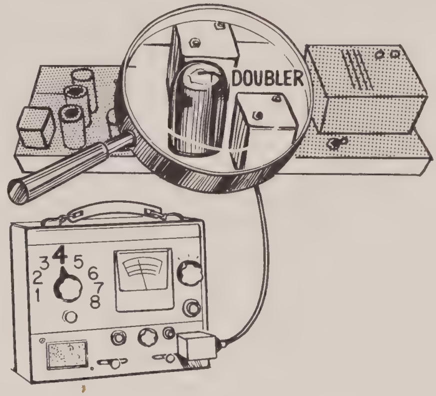
In addition to these tuned circuits between the buffer-doubler and the tripler, two other adjustments are provided in this portion of the transmitter. One of these is indicated by the arrow between the crystal and the oscillator. This control is a frequency adjustment and causes a relatively small change in the RF output of the oscillator. It does not have a noticeable effect upon the meter reading. The test set cannot be used to check the oscillator frequency adjustment--some other means must be employed.

The second adjustment--the deviation control at the clipper--determines the amount of modulation produced at the phase modulator. We know, however, that frequency or phase modulation has no effect on the amplitude of the RF, so again we must find another means for checking the setting of this control. (If the deviation control is set too high, the linearity of the phase modulator may be exceeded and small changes may be noted in the reading during modulation. This is due to the amplitude distortion introduced.)

The Doubler Grid-Meter Position 4

After the buffer-doubler output circuit is tuned to maximum in meter position 3, the switch is set to position 4 and the tripler-doubler coupling circuits are tuned. In this position, the meter shows the level of the signal at the grid of the doubler by indicating the amount of grid current. All the RF stages preceding the doubler--as well as the doubler grid itself--must be operating in order to establish a reading at this position.

Again the arrows indicate the tuned primary and secondary, respectively, of the coupling transformer; and again these adjustments should produce definite peak indications on the meter. (If the variations are sharply defined, it is permissible to "re-peak" the buffer-doubler circuits while observing the reading at position 4, for the level at the doubler grid will be affected by these circuits.)



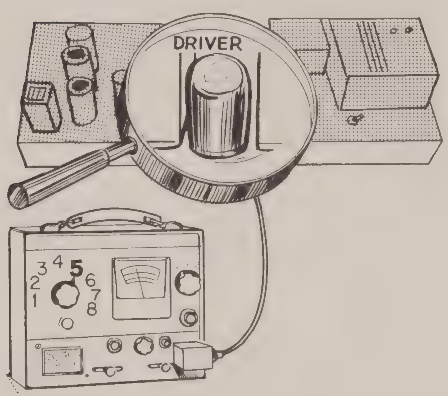
In Switch Position 4, the Motorola Test Set Indicates the RF Level at the Grid of the Doubler Stage.

Driver-Doubler Grid-Meter Position 5

Here we measure current at the grid of the driver stage, and the meter again becomes an output meter for the preceding stages. The plate tank of the doubler and the grid of the driver are tuned to resonance by obtaining a maximum meter reading--as before, definite peak indications are essential.

These peak indications must always be compared with the readings recommended by the manufacturer. To merely obtain a "peak" reading may not be enough if it is considerably lower than the minimum which is specified. Even more valuable perhaps is to make a comparison

between the reading secured at a particular position and the reading previously secured at the same position when the transmitter was known to be operating properly.



In Switch Position 5, the Motorola Test Set Indicates the RF Level at the Grid of the Driver Stage.

Power Amplifier Grid-Meter Position 6

At position 6, the meter is used for tuning the driver output circuits to resonance. The resonant condition must appear as peak readings, and again the peaks must be clearly defined.

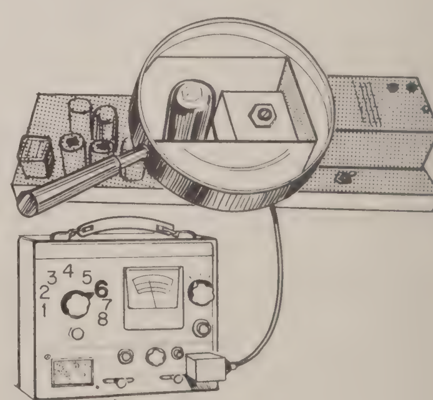
The reading in position 6 is not entirely the result of grid drive. Due to the fixed bias at the PA grid, there will always be some grid voltage, even when there is no signal input. This reading (always considerably lower than the normal reading) will depend upon the bias supply for the particular transmitter.

Final Amplifier; PA Meter Position

With the test set in the PA position, the meter indicates final amplifier plate current. This current is observed when adjusting the plate tank, the antenna coupling, and the antenna trimmer (represented by three arrows in the diagram).

Before tuning the plate tank, the antenna coupling is decreased (to minimum) and the antenna trimmer is adjusted to a position at which the reading on the meter is also minimum. (The HI-LO switch must remain at LO until the plate tank is at resonance.)

With minimum coupling to the antenna, the plate tank may now be adjusted to resonance. This will be indicated by a pronounced "dip" in the plate current reading. The value of current is of



In Switch Position 6, the Motorola Test Set Indicates the RF Level at the Grid of the Final Amplifier.

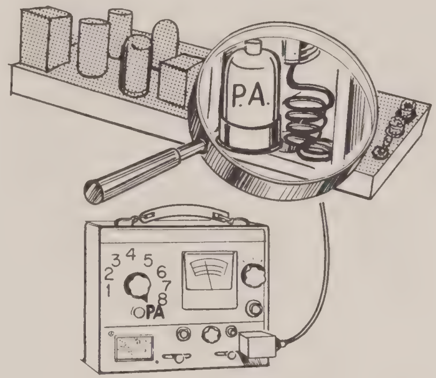
no consequence at this time, for it will increase as soon as the antenna is properly loaded.

Loading the Antenna

Any antenna loading procedure must take into consideration the maximum allowable plate current for the final tube. If the plate current is too high, tube life will be shortened. The antenna coupling is increased until the plate current is approximately one-half the value recommended in the alignment procedure. The antenna trimmer is then adjusted for maximum plate current. Should this bring the plate current above the recommended value, the antenna coupling must be reduced. Excessive plate current should never be corrected by means of the antenna trimmer; for maximum efficiency, the setting of the trimmer must remain at the point where maximum plate current is obtained.

So long as the antenna loading is being performed by observing the plate current meter, the plate tank circuit should never be readjusted for minimum. Because of the interaction of the antenna circuit with the plate tank, retuning the tank may result in a decrease of RF power in the antenna.

A second and more accurate method of loading the antenna makes use of a wattmeter. The wattmeter, when terminated into either the regular antenna or



In the "PA" Switch Position, the Motorola Test Set Indicates Plate Current of the Final Amplifier.

into a fixed impedance of the proper value, measures the RF power going to the antenna.

The loading is begun in much the same manner just described. The coupling is increased until the meter is approximately one-half the recommended plate current, and the antenna trimmer is adjusted for maximum plate current. The plate tank can now be retuned. In addition to watching the plate current meter, however, the adjustment is made for maximum power on the wattmeter. The wattmeter allows optimum setting to be made for the plate tank, the coupling and the antenna trimmer. These settings must always be for maximum power to the antenna, within the allowable maximum plate current.

Some wattmeters also indicate the power returning from the antenna to the final tank. If the antenna impedance is correct, the

power returning from the antenna to the final tank is negligible. Charts supplied with the wattmeter indicate the standing wave ratio on the transmission line for the amount of reflected power as compared to the transmitted power. If the standing wave ratio is too high, the antenna circuit is then very inefficient and a lot of power is being wasted.

In addition to poor transmitter coverage there is likely to be overheating within the final stage.

Frequency Adjustment

Although the frequency of the transmitter is determined by the oscillator frequency, assuming a fixed amount of frequency multiplication, the frequency of the transmitter is checked at the output rather than at the oscillator. If the operating frequency is not correct the oscillator can be adjusted to bring the transmitter to exact channel frequency. If it is necessary to change the operating frequency by an appreciable amount, the rest of the circuits must be repeaked for maximum efficiency and power output. In order to measure the operating frequency, however, the transmitter must first be aligned or there will be no output to measure.

The Desired Transmitter Operating Frequency is Established by Adjusting the Oscillator while Monitoring the Transmitter Output on a Frequency Meter.

The transmitter operating frequency is measured by means of special frequency meters; several types and makes are available. There will be described in detail in a later lesson dealing with unique test equipment.

The FCC requires each transmitter to be checked at least once every 6 months, both for frequency and deviation. A record or log of the measured frequency and deviation must be kept, along with the type and serial numbers of the equipment used to make the checks.

Deviation Adjustment

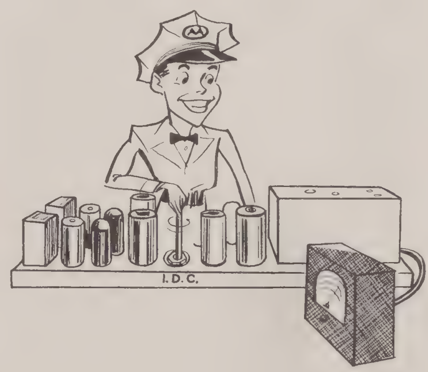
For optimum operation within any one system, it is important to keep the deviation of each transmitter within the prescribed limits. If the deviation is beyond the acceptance characteristics of a receiver, the signal will be weak and distorted. In noisy or weak-signal areas, moreover, the resulting signal-to-noise ratio may be very poor.

Thus for selfish reasons alone --apart from any consideration

of adjacent channel interference --overdeviation must be avoided. The deviation of a system, like the frequency, is usually measured at the transmitter. On Motorola transmitters, the amount of deviation is determined by the setting of the control located between the clipper output and the phase modulator. This control, known as the IDC control, is preset at the factory and secured by a locknut. If the deviation of a transmitter is found to be lower than normal, it is not enough to merely increase the control and make no further checks on the equipment.

The following example will illustrate this. The audio amplifier tube in a particular transmitter is becoming weak and the deviation is below normal. The serviceman increases the deviation setting and brings the operation back to normal. Let's assume that a short time later the tube becomes completely inoperative. The correct procedure is to substitute a new tube and reduce the deviation setting to normal, using a deviation meter. Let's see what could happen in such a situation. For one thing the serviceman making the second call may not be the same person who originally set the deviation higher. But even if he is the same person, he may forget that this is the same transmitter or that the deviation control has been advanced. In any case, the tube could be changed without the control being readjusted, and the resulting deviation is now higher than normal. Not only will the reception within the system be below normal, but the overdeviation may extend into adjacent channels and interfere with the signals of those channels.

Special deviation-measuring instruments are available, and they are also discussed in the lesson dealing with test equipment. The FCC requires that the instrument have a certain degree of accuracy. The deviation of all transmitters is checked each six months along with the frequency.



The Transmitter Deviation is Set by Adjusting the IDC Control and Monitoring the Transmitter Output on a Deviation Meter.

Oscillator Activity Adjustment

In some transmitters (not the one in figure 1) a tuned circuit included in the oscillator stage should be adjusted for maximum activity at the crystal frequency. The adjustment is checked by switching the meter to the oscillator stage, probably position 2 on the test set. The meter usual-

ly reads grid current, resonance being indicated by a maximum reading. When this type of circuit is provided, the oscillator is always peaked first before tuning any of the other stages.

Neutralization

The interelectrode capacitance of many amplifier tubes---especially those used in high-powered stages--sometimes permits too much feedback, causing the amplifier to oscillate. Since this oscillation affects both the tuning and the amount of plate current in the plate tank, it is usually necessary to use a neutralizing circuit in order to assure a stable amplifier. If a stage is to be completely neutralized, the voltage introduced by the neutralizing circuit and the feedback voltage due to the grid-plate interelectrode capacitance must have equal amplitudes and be of opposite phase.

The basic neutralizing procedure is essentially the same for all types of tubes and circuits. The filament of the amplifier tube should be lighted and excitation from the preceding stage fed to the grid circuit. There should be no plate or screen voltage applied to the amplifier and the coupling to the antenna must be minimum.

The immediate objective of the neutralizing process is to minimize the effects of the RF grid voltage fed from the input of the amplifier to its output circuit through the interelectrode capacitance of the tube. This is done by adjusting the neutralizing capacitor carefully, little by little, until the stage is neutralized.

Where neutralization procedures are required for the transmitter, they should be completed before other adjustments for the stage is attempted. In some transmitters the final stage has to be neutralized for each channel frequency. The instruction manual always describes these adjustments in detail and the recommended procedure must be followed at all times.

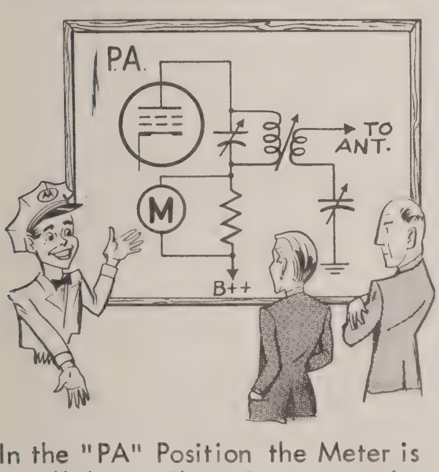
Testing for Neutralization

When the plate and screen supplies are removed from a stage, RF energy reaches the plate circuit through both the plate to grid interelectrode capacitance of the tube and through the external neutralizing circuit. When the energy from these two sources are of the same magnitude, however, the total RF energy in the plate tank is zero, for the two voltages oppose and cancel each other.

When the two voltages do not cancel completely there will still be some RF in the plate tank. If the plate tank is not at resonance, however, it does not absorb much of the available energy and hence does not "rob" the grid; if the plate tank is resonant, but the circuit is not neutralized, the tank then absorbs energy and the RF level at the grid decreases.

Thus, it is possible to determine whether or not a stage is neutralized (1) by noting the change (if any) of grid energy as the plate is tuned through resonance or (2) by checking for the presence of RF in the plate tank at resonance.

In order to check the grid current, the meter is switched to position 6. Then, with the high voltage supply to the final plate and screen removed and the coupling at minimum, but with a signal coming into the grid, the plate tank is tuned through resonance and the change of grid current noted. If the stage is completely or very nearly neutralized there will be little or no change of current as the plate tank is tuned in and out of resonance. If the plate tank adjustment causes an appreciable change of grid current, however, the stage is not properly neutralized.



In the "PA" Position the Meter is Parallel to a Shunt Resistor in the Transmitter and Indicates Plate Current.

Neutralization may be checked by using a low-voltage, low-current flashlight bulb, connected to a loop of wire and coupled to the plate tank coil. Again the plate and screen voltages are removed from the final, but the grid signal is applied. The plate tank is then tuned through resonance. If the circuit is neutralized there will be no indication in the lamp; if not, the lamp will glow.

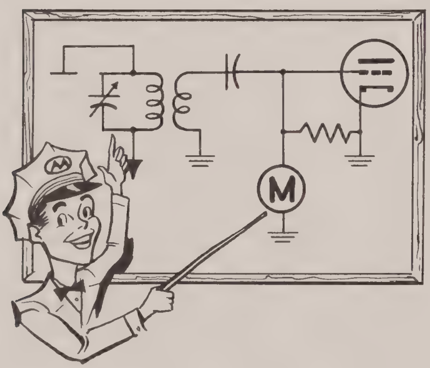
Trouble Shooting By Meter Reading

In addition to serving as a convenient means for aligning the transmitter, meter readings are a great aid in isolating any trouble to a particular stage or part of the transmitter.

Servicemen are in agreement that once the fault within a transmitter has been isolated to a particular section, the greatest part of the job is usually done. Routine voltage and resistance checks readily pin-point the unit causing trouble. Before the competent technician starts to trouble shoot the transmitter, however, he first makes sure that the trouble is not in some other part of the system. Where doubt exists as to which part of the system is at fault, he will first make additional system checks to definitely isolate the trouble. More will be said about this in a later section of the training.

Earlier in this lesson we mentioned the importance of compar-

ing the readings for the various meter positions with those previously recorded when the transmitter was operating properly. By knowing specifically which readings have changed, and to what extent, the exact portion of the transmitter which has changed its operational characteristics is pin-pointed. Unless a record has been kept of all the meter readings taken from time to time, however, this specific pin-pointing of changes may not be possible.



In the Transmitter, Most of the Circuits are Tuned to Resonance by Observing a Peak Indication in Grid Current at the Following Stage.

Let us, for example, suppose that the transmitter of figure 1 is "dead." Its messages are not heard by any receiver within the system, but other transmitters work normally. Also, the receiver which uses the same antenna as the transmitter operates normally so we can presume that the antenna is not at fault.

A transmitter may be dead because of the failure of its RF section (no carrier) or the fault may be with the audio section or microphone--perhaps the RF is not being modulated. Normal meter readings at positions 6 and PA usually indicate that there is an RF output. (If it becomes evident that the RF at the final is weak, the HI-LO switch is placed in the LO position before proceeding.) If the trouble is found to be in the RF section, as determined by a lack of output, it is then further isolated by switching to positions 3, 4, 5, and 6. If the reading at 3 is zero (or very low) we immediately know that the fault is in the oscillator, modulator or buffer.

If the RF power output is normal but no messages are getting through to receivers in the system, either the RF frequency is off channel or the modulation has failed. Before making a frequency check it would be more logical to begin with the audio tubes and the microphone.

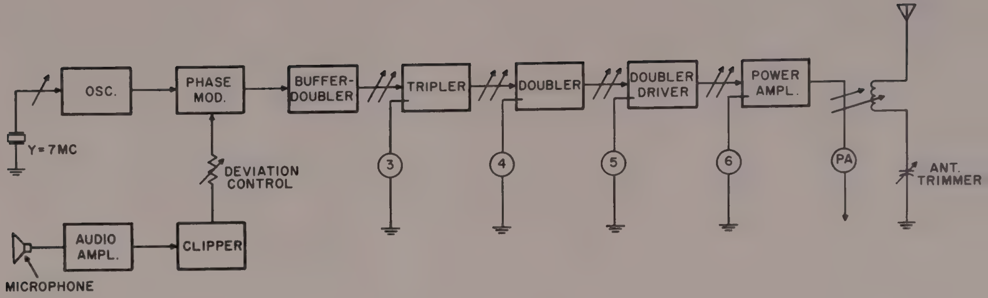
One of the most frequent complaints encountered when servicing transmitters is that the signals are weak; this is often the result of a weak RF output. Meter readings taken at positions 3, 4, 5, and 6 will quickly indicate the amount of drive at each stage within the transmitter, and again the offending stage is soon isolated. Weak tubes are the most frequent cause of trouble and the meter readings usually point to

the particular tube giving the trouble. Whenever a new tube is substituted, the transmitter alignment must be rechecked.

Another common fault in transmitters, particularly in higher powered sections, is the "soft" tube. A soft tube is a tube which becomes gassy. The readings are often near normal, but the output is weak. One means of detecting soft tubes is the alignment characteristics. A gassy tube often causes its output circuits to tune very broad so that a definite peak indication is difficult to obtain.

The above examples of common transmitter faults show the importance of using the meter in trouble shooting, and they have been presented solely for that purpose. It is not intended to discuss the complete trouble-shooting procedures of the transmitter at this time. (This information will be found in the next section of the training.) If you have a reasonable understanding of how meters are used in the FM transmitter, and their possibilities, you are ready to continue with the next assignment.

STUDENT NOTES



FM TRANSMITTER—METERING CIRCUITS
FIGURE 1

national

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RADIO COMMUNICATIONS

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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-8
FM TRANSMITTERS

Transmitter Specifications

MOTOROLA TRAINING INSTITUTE

LESSON TA-8
FM TRANSMITTERS

Transmitter Specifications

—one of a series of lessons on two-way FM communications—

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TRANSMITTER SPECIFICATIONS

LESSON TA-8

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There is no better means than two-way radio to deploy one's sales or service forces in a large metropolitan area. The combination of city map, radio control console and order box is found in thousands of dispatch rooms.

TRANSMITTER SPECIFICATIONS

Lesson TA-8

Introduction

In the lesson on receiver specifications, it was pointed out that the analysis of some problems may require an intelligent interpretation of the "specs." This reasoning applies equally well to the transmitter and to its technical specifications. Thus it is important to the technician that he become familiar with the various specs of the two-way FM communications transmitter.

The following example will make this clear. Original assignments in the high band were made at 60-kc channel spacings and deviation and frequency stability requirements were established accordingly. In 1958, however, the FCC established split-channel operation (30-kc channel spacing) for many of the services within the high band. New systems being placed in operation must conform to split-channel requirements, and existing systems must be converted to this mode of operation by 1963. This means that many of the transmitters now in operation (which do not meet the requirements) must be either converted or replaced. The required frequency stability is .0005% and the deviation is ±5kc.

From the above it can be seen that a transmitter must be operated under certain specified conditions; otherwise its performance will be unsatisfactory. The technician must have the ability to recognize the significance of each technical specification concerning the transmitter if he is to determine whether or not the equipment is performing in a normal manner. Equipment which is being misused cannot be expected to yield satisfactory results.

Many transmitter specifications are not governed directly by the FCC, for the FCC is concerned only with the transmitter "output." The industry, however, recognizing the importance of standardization, has evolved a set of standards for designating and measuring all types of electronic equipment. The industry is represented by the Electronic Industries Association (formerly RMA, RTMA and RETMA) and this group has formulated standards which have come to be accepted by everyone concerned.

Figure 1 describes a typical Motorola transmitter designed for either mobile or base station applications. Several types of final stages are available within one general chassis arrangement depending upon the required power output. In this lesson we shall discuss the technical specifica-

tions of this particular transmitter.

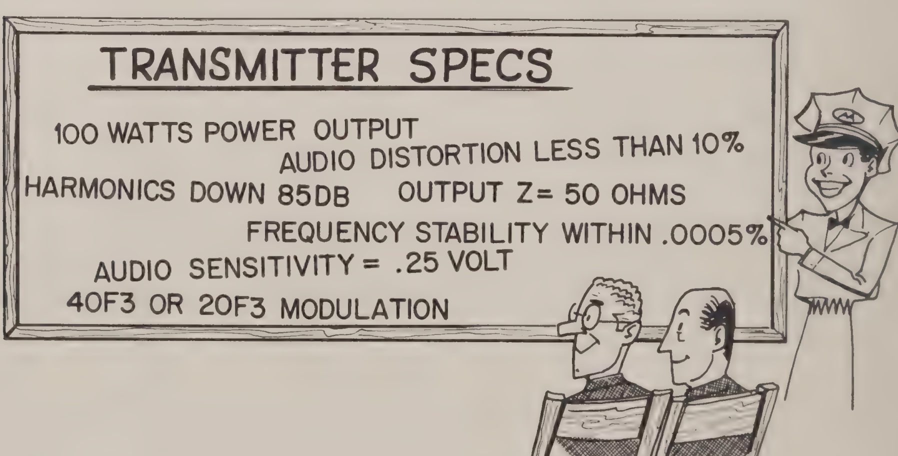
Frequency Range

The transmitter described in figure 1 can be operated on any channel assignment between 144 and 174 mc, and it will remain within its minimum specifications over this entire range of frequencies. The output frequency of the transmitter is the 24th harmonic of the oscillator frequency and the operating channel depends upon the crystal selected for the oscillator. The correct crystal frequency may be determined readily by dividing the desired channel frequency by 24.

Power Output

Figure 1 indicates that the power output of the transmitter may vary between 50 and 60 watts, depending upon the operating frequency. Due to the lowered efficiency of the final and other stages at higher frequencies, we may anticipate a decrease in power output for the upper end of the operating range. Thus, for frequencies up to 167 mc the transmitter will provide at least 60 watts of RF power but between 167 and 174 mc, only 50 watts can be expected.

The FCC license for a particular transmitter will usually specify the allowable power input to the final stage rather than the RF power output. Thus in transmitter specifications, it is possible to find two different types of power ratings. One of these, the DC power input to the final plate circuit, is the product of the plate voltage and the plate current. The other refers to the RF power output, which is the power taken from the final stage and transferred to the antenna.



To be Successful, the Two-Way Radio Service Technician must be Well Acquainted with Transmitter Specifications.

The EIA (Electronics Industries Association) defines the RF power output rating of a transmitter as "the power available at the output terminals of the transmitter when the output terminals are terminated to the normal load circuit or to a circuit equivalent thereto." As required by EIA, continuous power ratings must be made under test procedures over a 24-hour period without dropping below the rated value.

For most equipment, however, the duty cycle is not continuous. Instead, the transmitter is on for short periods of time, during which a message is being transmitted. At all other times, the two-way communications equipment is in standby (or receive) condition. Thus, it is almost standard procedure to list these transmitters according to their "intermittent" power capabilities. The intermittent power rating is the "full load output under normal recommended loading conditions, using a cycle of one minute on, then four minutes off for a period of eight hours followed by three continuous test cycles of five minutes on, fifteen minutes off."

Undesired Radiations

The three types of signals which appear at the output of the transmitter are (1) the desired channel signal---including the modulation components, (2) harmonic radiations, which are always multiples of the channel frequency, and (3) spurious radiations, which include all radiations other than the channel signals and the harmonics. Both the harmonic and the spurious radiations are highly undesirable and must be minimized. Harmonic radiations are effectively suppressed by the harmonic filter. Spurious radiations, however, which may occur above, below, or even within the operating channel frequency range must be controlled by other means, good design in particular.

The FCC has placed definite limitations on the amount of harmonic and spurious energy that may be radiated from a particular transmitter, and this amount varies according to the power capability of each transmitter. See the following table.

PLATE INPUT POWER TO FINAL STAGE	ATTENUATION
3 watts or less	40 db
From 3 to 25 watts	60 db
From 25 to 150 watts	60 db
150 watts and over	70 db

The attenuation figures indicate the maximum level of energy allowed for either the harmonic or the spurious radiation---not their combined values. The 50-60 watt transmitter described in figure 1 has a plate input power of less than 150 watts, so the attenuation for either the harmonic or the spurious radiations must be at least 60 db. This db ratio refers to the amount of voltage produced at the output, across a standard load impedance,

compared to the voltage produced by the channel frequency. (This test is difficult to make and requires the use of specialized equipment. Therefore it is not practical for the average serviceman.)

The transmitter of figure 1 has a guaranteed (minimum) attenuation of 70 db for all spurious radiations, but only a 60-db attenuation is required by the FCC. This means the spurious radiations are actually 10 db lower than required. (An attenuation of 10 db in power represents a voltage ratio of about 3 to 1.)

The harmonic output of the transmitter is specified in figure 1 to be at least 60 db below the carrier. This amount, required by the FCC, is a practical limitation and usually provides freedom from unnecessary interference.

Frequency Stability

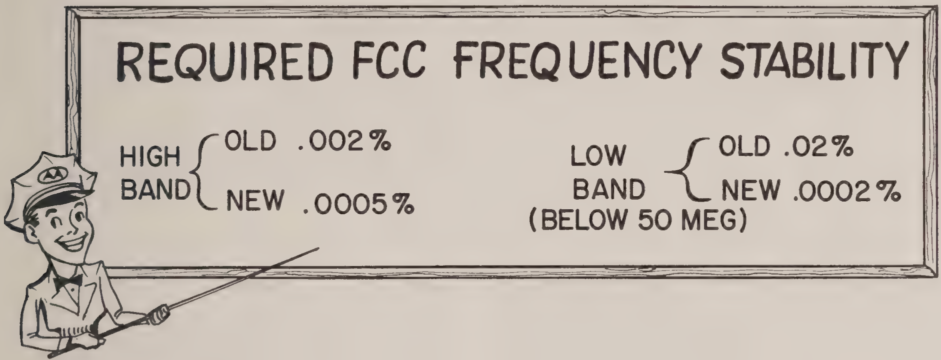
Carrier frequency stability is the ability of a transmitter to maintain an assigned carrier frequency. The carrier frequency stability is expressed as the maximum percentage of the assigned frequency that the center frequency may deviate from that frequency in the absence of modulation. Typical stabilities are 0.002% for the 25-50 mc band and 0.0005% for the 50-1000 mc band. These are the stabilities recently adopted by the FCC. They are not effective immediately for all existing equipment, although they apply directly to new systems. Some equipment now in use does not have to conform to these ratings until 1963.

According to the above figures, the carrier frequency of a transmitter operating at 150 mc may vary as much as 750 cycles above or below the assigned channel frequency. (150 mc times 0.0005% equals 750 cycles.) The transmitter of figure 1 readily maintains this 0.0005% accuracy for temperatures ranging between -30° C and $+60^{\circ}$ C.

For a check on the frequency stability, the reference frequency is noted at 25° C. The frequency at all other temperatures within the specified range must then remain within approximately 750 cycles of this reference frequency. The FCC requires that the equipment used to measure the carrier frequency must have an accuracy of at least twice the stability of the minimum to be measured.

These stabilities apply only to fixed and mobile transmitters rated at more than three watts of plate input power. Mobile transmitters within the 25-1000 mc band which are rated at three watts or less have a required stability of 0.005%.

The 0.0005% stability rating for the transmitter of figure 1 makes it readily adaptable to split-channel operation. Thus when the FCC authorizes the split-channel assignments (with 30-kc spacings), these transmitters will have the necessary stability to allow easy



The New FCC Frequency Stability Requirements Requires a Review of the "Specs" of the Equipment Being Serviced.

conversion to such operation. If the transmitter has not been provided with this degree of stability, the necessary conversion may require additional changes within the oscillator stage.

Transmitters are sometimes rated directly as to how many cycles the carrier will change from the assigned frequency. Several Motorola 450-mc transmitters, for example, are guaranteed to maintain their frequency within 2.5 kc of the assigned channel frequency. This is approximately 0.0005%, the same as the ratings for the high-band transmitters. In all these Motorola transmitters, the high degree of stability is achieved by maintaining the crystal itself at a nearly uniform temperature within a thermostatically controlled oven.

Output Impedance

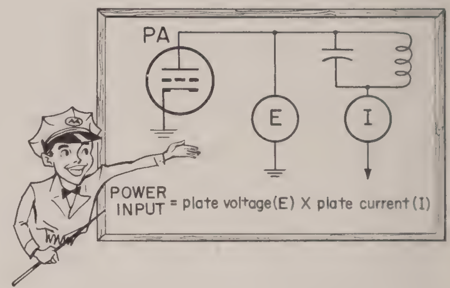
The power output which is actually radiated from any transmitting antenna will be maximum only when there is an impedance match between the transmitter and the antenna system. Without this impedance match, the full power output of the transmitter cannot be realized. The rated impedance of most antenna systems used in FM two-way communications is 50 ohms. Therefore, the transmitter is designed to load into this value of impedance.

When there is a mismatch between the impedance of the antenna, the transmission line and the final amplifier, some of the energy is returned from the antenna back to the final. In addition to reducing the power radiated from the antenna, this results in more RF loss and a higher plate dissipation in the final tube.

A perfect impedance match is usually difficult to obtain---particularly in mobile applications. However, if the impedance match

is reasonably good, the amount of power reflected from the antenna will be small and such a system will prove satisfactory in its performance.

There is no practical method by which the serviceman can actually measure the impedance of the transmitter and antenna system. By determining the standing wave ratio, however, the amount of mismatch can be determined rather closely. Any wattmeter which is capable of measuring both forward and reverse RF power in the transmission line will provide an immediate check on the forward power and reflected power. With this information, the impedance match and standing wave ratio are determined from charts or conversion formulas.



FCC Designations of Transmitter Power Usually Give the Maximum Allowed Power Input to the Last Stage Rather than the Maximum Allowed RF Power Output.

Modulation

The modulation of the transmitter of figure 1 is described as "40 F3." This means that the bandwidth is 40 kc and the type of modulation is F3. Type F3 modulation, according to the FCC, is the transmission of voice messages by means of frequency modulation. For licensing purposes, 15 kc deviation with a 3000 cps audio signal is designated by the FCC as being type 40 F3 modulation. (For split channel operation the modulation designation would be 20 F3.)

Figure 1 indicates that this particular transmitter may be frequency modulated, with a deviation of either 15 kc or 5 kc. This is determined by the adjustment of the deviation control with a 1000 cps signal applied. Full deviation of 5 or 15 kc, whichever is established for the system, is sometimes referred to as "100% modulation" in FM systems, but it must be noted that this is not the same as the 100% modulation rating used in connection with AM systems.

In specifying various modulation conditions, the EIA has established certain standards, one of which is "standard test modulation." This refers to a 1000-cps signal producing two-thirds of the full rated system deviation.

Audio Input Level

If the transmitter is to be fully deviated by the audio input signal,

a certain amount of voltage must be supplied. The transmitter of figure 1 can be fully modulated with inputs of either 0.25 volt or 0.18 volt. This choice of signal level is provided by a tapped arrangement at the input, each input having a different modulating sensitivity.

With a microphone having a relatively low output, a carbon handset, for example, the higher sensitivity tap (0.18 volt) is used and the full output from the microphone is applied to the transmitter input. If the microphone has an output approaching .25 volt, however, the less sensitive tap (0.25 volt) is used (only 0.18 volt of the microphone output reaches the amplifier grid). Thus, by employing the correct tap, the transmitter will be correctly modulated, whichever microphone is used. If one microphone is substituted for the other, all that has to be done is to change the sensitivity tap. The use of alternate taps for microphones of different levels is a means of keeping the input signal applied to the transmitter audio circuits at the desired level without excessive clipping of the audio signal.

When transistorized microphones are used, the output level is 0.25 volt. This is the microphone input value found in most transmitters. Whenever a microphone having a lower output is used, the alternate connection (to the more sensitive tap) must be made. In remote control applications, also, where the line level is not sufficiently high to operate from the 0.25 volt input, the connection must be made at the 0.18 volt tap and the input adjusted accordingly.

FM Noise and Hum Level

FM noise and hum is the ratio of normal deviation to residual frequency deviation (the latter due to noise, hum, etc.). This is determined by the ratio of the standard test modulation (1000 cps at two-thirds the full deviation) to the residual frequency modulation.

The FM noise and hum level for both stationary and mobile transmitters shall be 40 db below standard test modulation where the full rated system deviation is 15 kc. (If the full rated system deviation is less than 15 kc, the FM noise and hum level ratio may be proportionately reduced.)

This measurement is made with a standard test receiver. The transmitter output is first recorded on the receiver under standard test conditions. The modulation is then removed from the transmitter and the change in output level at the receiver is noted. This ratio, stated in decibels, is the FM noise and hum level.

Audio Response

The EIA defines the audio frequency response of the transmitter as the degree of closeness to which the frequency deviation of

the transmitter follows a 6 db per octave pre-emphasis characteristic (with constant amplitude audio frequency input) over a continuous frequency range. It shall not vary more than +1 db or -3 db from a true 6 db octave pre-emphasis characteristic from 300 to 3000 cps, referenced to the 1000 cps level. The audio response of the transmitter in figure 1 meets these specifications.

In Compliance with FCC Regulations, the Deviation of Many Two-Way Radio Systems Has Already Been Lowered from the Former ±15KC to ±5KC.

In order to check audio response, the transmitter is operated under standard test conditions and its output is monitored with a frequency deviation monitor or a calibrated test receiver. A 1000-cps sinewave voltage is applied through a dummy microphone circuit and adjusted for 30 percent of the full rated system deviation. Keeping the audio level constant, the modulating signal is varied between 300 and 3000 cps and the amount of deviation is recorded. The modulation limiter must be operative during this test, and adjusted according to the manufacturer's instructions.

The above specification of the transmitter audio frequency response is limited to the range of frequencies employed for voice transmission, and there is no measure of the control imposed upon signals above 3000 cps. The high-frequency sideband content must be limited, however, and a suitable filter must therefore be installed in the audio supply line to the phase modulator. This is specified in a recent FCC ruling on "split channel operation," which applies to all two-way communications transmitters. Basically, the FCC requires that the transmitter shall include a filter which has an attenuation of at least 12 db per octave for frequencies above 3000 cps.

This filter need not affect the frequencies within the transmitted voice range of 300-3000 cps, but the attenuation is rather severe above 3000 cps. (The amount of splatter into the adjacent channels is thus held to a minimum.) An attenuation of 12 db represents a voltage ration of 4 to 1. A 6-kc signal, for example, will produce only one-fourth as much voltage at the phase modulator as a 3-kc signal, the amplitude of the input being the same in each case.

The FCC designates the 12 db per octave characteristic of the filter as follows:

For frequencies between 3 kc and 15 kc, the filter shall provide an attenuation greater than the attenuation at 1 kc by at least 40 log (f/3) decibels, where "f" is the audio frequency in kilocycles. In addition, for signals above 15 kc, the attenuation shall be at least 28 db greater than the attenuation at 1 kc.

Perhaps we can best understand the effect of both the preemphasis of the phase modulator and the attenuation of the filter by examining the net audio response resulting at the output of the transmitter. See figure 2. (This curve is obtained by using a standard receiver.)

The dashed lines extending between 300 and 3000 cps show the EIA requirements of a 6 db per octave preemphasis, within + 1 db and - 3 db. The solid line showing the response of the transmitter is within the limits for the entire voice range.

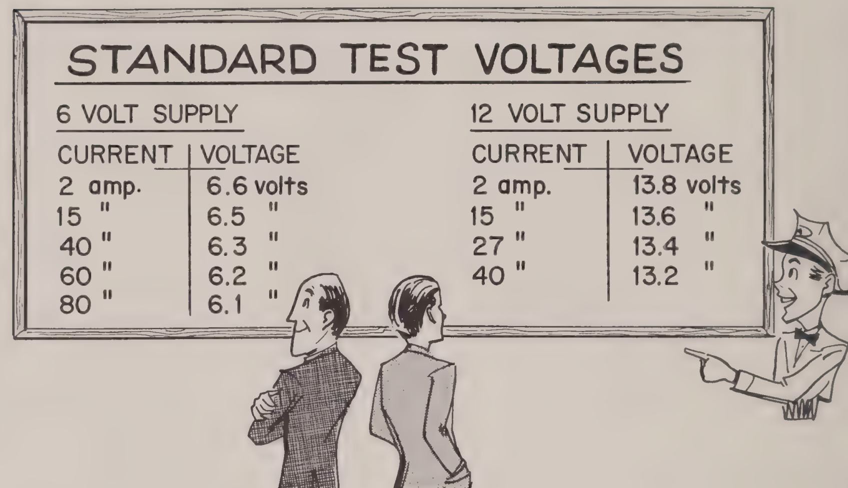
Beyond 3000 cps the attenuation is very pronounced. This is due to the "splatter choke" in the transmitter. The attenuation of the signals above 3 kc is at least 16 db per octave, which is considerably better than the 12 db minimum specified by the FCC. The phase modulator, of course, adds its natural preemphasis of 6 db per octave, but the net effect upon these higher frequencies is 10-12 db per octave. At 3 kc the signal level is approximately +6 db. One octave higher (6 kc) the level is -6 db, a 12 db difference.

The FCC also requires the filter to attenuate signals above 15 kc by at least 28 db more than the attenuation at 3 kc. The level (in figure 2) at 15 kc is -29 db, which is 35 db lower than the +6 db at 3 kc. Remembering that the modulator adds preemphasis to these higher frequencies, the attenuation by the filter is even greater than the 35 db shown.

Audio Harmonic Distortion

"Audio frequency harmonic distortion" is a change in the harmonic content of the audio input signal when it passes through the transmitter. The EIA limits the maximum allowable distortion to 10%.

In order to make this check, the transmitter must first be ad-



Transmitter Specifications, Such As Power Output and Frequency Stability, Assume a Specific and Standardized Amount of Applied Voltage.

justed for full rated system deviation in accordance with manufacturer's instructions. A sinewave having less than 1% distortion at 1000 cps is then applied to the transmitter at a level which will produce two-thirds of full rated system deviation. The standard receiver is now tuned to the carrier frequency and the distortion in the receiver output is measured.

While the EIA allows a maximum of 10% harmonic distortion of the audio signal within the transmitter, the unit described in figure 1 has a distortion of less than 5%.

When making this distortion test, it will be found convenient to include a check on modulation limiting, which is a function of the clipper-limiter stage. In order to make this check, the audio signal is first increased 20 db above the level needed to produce two-thirds system deviation. (20 db is a 10 to 1 voltage ratio.) Then, when the signal varies between 300 and 3000 cps, the resulting modulation should not exceed the full rated system deviation.

Primary Power [1]

The transmitter and receiver which make up a complete communications system are often operated from the same power supply. It is therefore common practice to give their combined power requirements rather than the power requirements for each unit separately. The transmitter and receiver are not required to be in operation at the same time, however, and this makes it possible to switch the B supply between the two units---reducing the total

1. Primary Power and Power Supplies are discussed in the next three lessons.

drain from the primary power source. The transmitter usually requires more plate current than the receiver, so two figures must be given for primary power drain ---one for standby (when the receiver is on), and one for transmit. The transmitter of figure 1 has a drain of 14.8 amperes from a 6-volt battery when receiving and 80 amperes when transmitting.

Where equipment is designed to operate from a supply of either 6 or 12 volts, current requirements are given for both systems. For a 12-volt source the transmitter of figure 1 has a drain of 7.5 amperes on standby and 43 amperes on transmit.

Power Supply Test Voltage

There are standard test voltages to be used in checking equipment while operating from 6 and 12 volt supplies, depending upon the current supplied to the equipment. These voltages (not shown in figure 1) are as follows:

Nominal 6-Volt Power Supply

Operating Current	Test Voltage
2A	6.6V
15A	6.5V
40A	6.3V
60A	6.2V
80A	6.1V

Nominal 12-Volt Power Supply

Operating Current	Test Voltage
2A	13.8V
15A	13.6V
27A	13.4V
40A	13.2V

Additional Specifications

Additional specifications (such as size, type of mounting, and cabling) which are important to systems installations are available from the specs sheets. Additional checks and tests should also be made on the transmitter so that it will be satisfactory when operated under all anticipated conditions. These tests have to do largely with vibration and shock, humidity, and temperature.

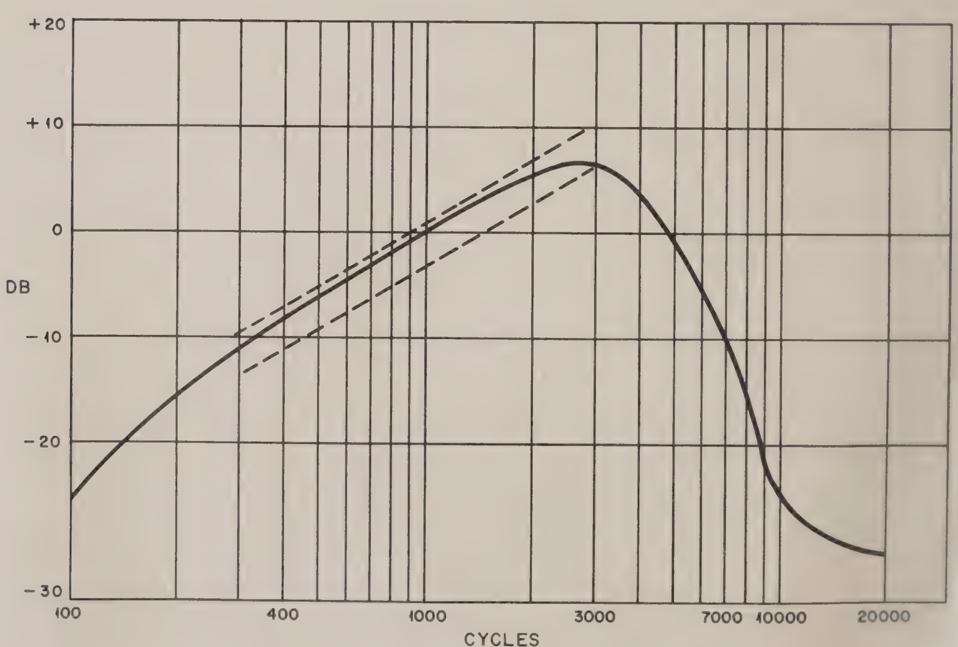
STUDENT NOTES

STUDENT NOTES

RF POWER OUTPUT	Model TA192--60 watts min.-144 to 167 mc. 50 watts min.-167 to 174 mc.
SPURIOUS AND HARMONIC EMISSIONS	spurious more than 70 db. below carrier harmonics more than 60 db. below carrier
CRYSTAL MULTIPLICATION	24 times
FREQUENCY STABILITY AND TEMPERATURE RANGE	oven type crystal unit maintains carrier within ±.0005% of assigned center frequency from -30°C. to +60°C. ambient (+25°C. reference)
OUTPUT IMPEDANCE	50 ohms
MODULATION	40F3: ±15 kc,; or ±5 kc. for 100% at 1000 cps.
AUDIO INPUT LEVEL	0.25 volt ±3 db. for 100% at 1000 cps (approx. -17 db) 0.18 volt ±3 db. for 100% at 1000 cps (approx. -20 db)
FM NOISE	-40 db. below ±10 kc deviation at 1000 cps
AUDIO RESPONSE	+1, -3 db of 6 db/octave pre-emphasis characteristic from 300-3000 cps.
AUDIO DISTORTION	less than 5% at 1000 cps.; 10 kc. deviation

BATTERY DRAIN (in amps)	6 VDC	12 VDC
standby	14.8	7.5
transmit	80	43

TRANSMITTER SPECIFICATIONS
FIGURE 1



TRANSMITTER AUDIO RESPONSE
FIGURE 2

national

MOTOROLA
RADIO COMMUNICATIONS

service

LESSON TA-9
POWER SUPPLIES

Power Supplies

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LESSON TA-9
POWER SUPPLIES

Power Supplies

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

POWER-SUPPLIES---GENERAL

LESSON TA-9

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Modern construction crews need radio to schedule supplies and workmen. Real growth of radio in this field resulted when the Business Service was established in 1958.

POWER-SUPPLIES---GENERAL

Lesson TA-9

Introduction

The preceding lessons of this training have been concerned mainly with the receivers and transmitters used in two-way FM communications systems; little has been said about their power supplies. We are now ready to become acquainted with the various types of power supplies used in such systems.

Although the power supply may be located on a separate chassis and separated physically from the receiver and transmitter, it must be regarded as an integral part of these units. Unless the supply makes available the required voltages and currents neither the receiver nor the transmitter will operate as intended. The two lessons following this one will be concerned with specific power supply circuits (vibrators, transistors, etc.) and their operation. In the present lesson, we shall confine our study to the principles underlying all power supplies and to power supply requirements in general.

Primary Power Requirements

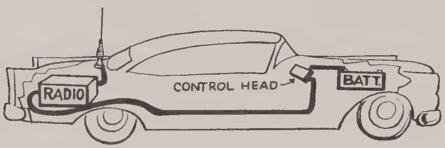
Since most two-way communications equipment is designed for use in trucks, taxicabs and other mobile units, the efficiency of the power supply is very important. The capacity of the primary power source (battery) is limited and it is imperative that this power be transferred to the receiver or transmitter with minimum loss.

Types of Power Supplies

Power supplies are often classified according to the system used for converting the primary power to the required DC voltages. Four types of supplies have been used with reasonable satisfaction in mobile equipment. They are known respectively as vibrator, dynamotor, alternator and transistorized supplies. The two most often found, at present, are the vibrator and dynamotor types.

For low and medium power and where size, weight and economy are the major considerations, the vibrator supply is quite satisfactory. For high-power transmitters (50-100 watts), it is more advisable to use the dynamotor supply, or a combination vibrator and dynamotor supply. Vibrators do not have long life where they must deliver a large amount of power for any length of time and, under these circumstances, the

dynamotor is more reliable and trouble-free. The dynamotor is a combination motor-generator which operates from the car battery and supplies a high voltage DC to the final stages of the transmitter. A vibrator supply is usually included with the dynamotor to furnish the lower B voltage to the other stages of the transmitter (and to the receiver).*



The Power to Operate the Receiver and Transmitter of the Mobile Two-Way Radio is Furnished by the Electrical System (Battery).

Another system makes use of an alternator operated from the fan belt of the motor in the vehicle. The AC output from the alternator is converted by a suitable transformer to 110 volts AC. The equipment power supply is of the conventional AC type. This system is comparatively expensive, inefficient and bulky. As a result, it is seldom encountered in modern equipment.

The fourth type of power supply is the transistorized unit. Two power transistors perform the same basic function as the vibrator. Improvements in both the power handling capability of the transistor and in transistorized power supply circuitry have made it possible for the transistorized supply to replace either the vibrator or the higher-powered dynamotor supply. Because of its compactness, improved efficiency and promise of long life, the transistorized supply will probably replace all other supplies in the near future. The circuitry and operation of these supplies will be discussed in the next two lessons.

The Primary Source - Filament Operation

We normally think of power supplies as operating from source voltages which are too high to operate the filaments of the average tube. This involves incorporating some means of reducing the voltage to that required by the filaments. In the case of mobile unit, however, the primary source is itself usually 6 or 12 volts, and this makes it possible to operate the tube filaments directly from the battery. For 12-volt systems, 6-volt tube filaments may be connected in a series-parallel arrangement and placed directly across the source. Control relays, pilot lamps and crystal oven heaters are also operated directly from the primary power. This practice of using the primary power directly for the operation of relays, tube filaments and oven heaters is most efficient as it avoids power losses due to conversion.

Where the filament power is controlled by the same switch that

* Transistorized supplies capable of operating high-power transmitters are now replacing the dynamotor type supply.

turns on the equipment, all tubes will be lit and ready for operation at all times. This allows immediate changeover from standby to transmit and back again without requiring any warm-up period.

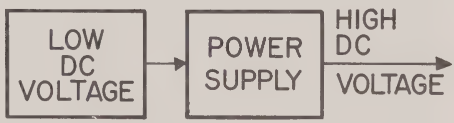
The primary circuit is not fused internally in the main housing, but protection from direct shorts is provided by means of the master fuse in the cable to the battery.

6/12 Volt Operation

A few years ago, when manufacturers decided to change 6-volt ignition systems in cars to 12-volts, manufacturers of electronic equipment were confronted with two problems. First, there was a lot of equipment already installed in 6-volt cars and it would be necessary to convert this equipment to 12-volt operation before it could be installed in the new cars. Second, all new equipment would have to be designed so that it could be interchanged from one type of power to another without modification.

Several solutions to the problem of converting the existing 6-volt equipment were available, but not all of them were satisfactory. The procedure to be adopted depended upon whether the equipment could be converted permanently, or whether it must be interchangeable between 6 and 12 volt systems.

Motorola has two practical solutions to the problem of converting older equipment for 12-volt operation. In order to operate the radio from either a 6-volt or a 12-volt source, special converters are installed. These converters incorporate dual synchronous vibrators and a transformer, producing a 6-volt DC output. For permanent conversions, most Motorola equipment lends itself to comparatively simple and inexpensive circuit changes, allowing the radio to be operated directly from the 12-volt line.



Basically, the Power Supply in the Mobile Two-Way Radio Alters the Low-Voltage DC of the Battery to a High DC Voltage.

The problem of designing new equipment for either 6 or 12 volt operation without modification is particularly important in large fleet applications where a complete unit (receiver, transmitter and power supply) is often interchanged between cars. Where modifications are necessary, it is obviously too easy to put the wrong unit in a vehicle. In order to be entirely satisfactory, the equipment had to be interchangeable between 6 and 12 volt vehicles without modification.[1]

1. See "Radio Equipment hich Meets the Challenge of 6 and 12 Volt Vehicles," reference T-9A.

"Twin-V" Operation

With this idea in mind, Motorola engineers set about designing the equipment. Because the power cables are normally a permanent part of an installation and remain in a car even when the unit is changed from one car to another, a practicable solution was found by using two different cables, one for 6-volt installations and the other for 12 volts. All modifications are then made in the cabling; the receiver, transmitter and power supply chassis remain the same. This system is called "Twin-V," indicating the equipment will operate from either voltage.

Figure 1A shows the connections to the power supply from both 6 and 12 volt batteries. Where 6 volts is to be used, terminals 1 and 3 of the power plug are connected together and the ungrounded sided of the 6-volt supply is applied to the corresponding terminals of the power supply plug. For 12-volt operation, the ungrounded side of the 12-volt supply is available at terminals 1 and 4; terminals 2 and 3 are tied together, and only terminal 5 is grounded. The operation of this primary circuit for either 6 or 12 volts is easier to follow in figures 1 B (6-volt operation) and 1 C (12-volt operation).

Terminal "A" of the filament circuit is grounded for 6-volt operation (figure 1B), and the bottom line "G" is grounded at all times. This places all filaments, relays, pilot lamps and oven heaters in parallel across the 6-volt battery.

The vibrator transformer has two separate 6-volt primary windings. One side of the 6-volt battery is connected to the center tap of each of these windings in figure 1B. The other side of the battery is grounded. The two ends of each primary winding are alternately connected to ground through the vibrator contacts. The vibrator has two mechanically ganged but electrically separated armatures, each complete with a set of contacts, thus completing the circuit through the primary windings to ground.

With the equipment turned on, the drive coil is energized and the armatures move "up." The current takes the path shown by the solid arrow, through the upper half of each primary winding. The two windings, or halves, are thus connected in parallel.

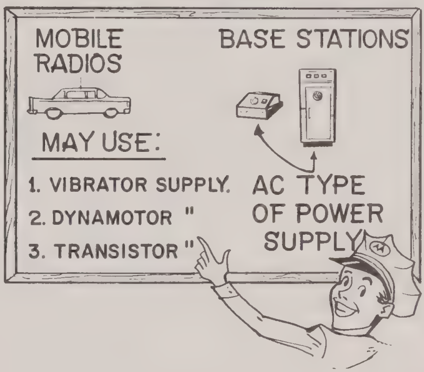
As soon as the armature swings up, the circuit to the drive coil is broken and the armature swings in the opposite direction. The circuit through the lower half of each primary winding is now completed through the vibrator contacts (shown by the broken arrows). When the armatures swing downward, however, the circuit to the drive coil is again completed and the armatures are again pulled upward. This action continues, usually at a rate of about 110 cycles per second.

The currents through the primary windings are first in one direction and then in the opposite direction as far as the magnetic field is concerned, and this produces an AC voltage in the secondary. Because the two primary windings are in parallel, and only one half of each primary is used at a time, the turns ratio of the transformer is based on one primary winding instead of two. This turns ratio is used in connection with the primary voltage to determine the secondary voltage.

In figure 1C, one side of the 12-volt battery is applied (1) to the center tap of primary P1, and (2) to terminal A of the filament circuit. The other side of the battery is grounded as before. Assuming that the load required by the "A-B" section of the filament circuit is the same as that of the "B-G" section, the 12 volts will be divided equally between the two sections. Each filament, pilot lamp, relay and heater will be supplied with 6 volts.

The halves of the two primary windings are now connected in series with each other across the 12-volt battery. When the armature contacts are "up," the current takes the path shown by the solid arrows; the broken arrows show the path with the armatures "down." In each instance, the current follows a series path through the primary windings, and the voltage across each primary will be one-half that of the battery voltage.

With the primaries now in series, the number of primary turns is effectively doubled and the turns ratio is now half of what it was for 6-volt operation. The primary voltage is now doubled, however, and the secondary voltage thus remains the same as for 6-volt operation.



Mobile Radios Use Vibrator, Dynamotor and Transistor Types of Power Supplies. Base Stations Almost Always Have an AC Supply.

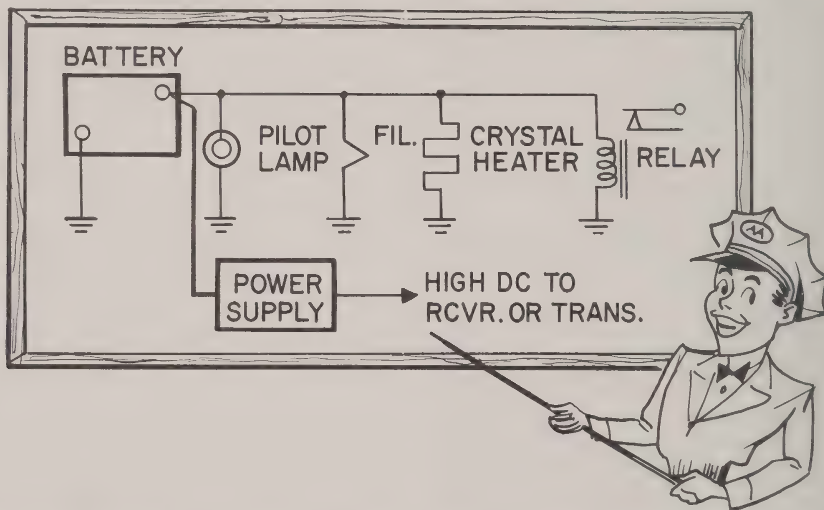
Stability of the Filament String

The system we have been discussing is mainly one of 6-volt operation, with provision for dividing a 12-volt supply evenly into two 6-volt sections. When the power supply is operated from a 12-volt battery, the cable plug connection between terminals 2 and 3 (figure 1A) place the two windings in series with each other and the action is the same as if a single winding with a center tap were used. An even division of the 12 volts is maintained across

the two windings so that each winding has 6 volts. The currents through each filament section might not be perfectly balanced because of an uneven load, but the commutating action of the windings and vibrator will stabilize the voltages.

mary P1 in parallel with filament section AB and primary P2 in parallel with filament section BG.

Assume that the crystal heater between A and B is turned on by its controlling thermostat, creating an unbalance between the two



In the Mobile Radio, Tube Filaments, Pilot Lights, Crystal Heaters and Relays Usually Operate Directly from the Battery. Only the Plate and Screen Circuits of the Tubes Require a Power Supply.

The commutation, which maintains nearly equal voltages when the filament strings are unbalanced, is due to autotransformer action of the two primary windings. Either winding will act as a primary--the other is the secondary. If the voltage of one winding increases, the voltage of the other winding must also increase. It is this action which maintains even voltages at the filaments. Interconnections between the transformer primary circuit and the filaments (figure 1C) place pri-

filament currents. The additional current must pass through the BG section and tends to increase that voltage.

This higher voltage at BG causes the voltage at AB to increase, however, due to the autotransformer action of the primaries. The battery does not allow both filament voltages to increase, for it maintains an essentially constant voltage across the entire circuit. As a result the AB and BG voltages must remain nearly equal.

12-Volt Regulator

Experience has shown that under certain conditions, the voltage available from the so-called 12-volt ignition system may be as high as 15-16 volts. While this excessive voltage may be the result of an improperly adjusted regulator in the car's ignition system, a high voltage is normal when the battery is cold and in a fully charged condition.[2]

If the primary voltage is too high, however, damage may result to the tube filaments and other components. It is thus desirable to limit the voltage applied to the two-way radio equipment. Motorola has designed a regulator which controls this voltage only---it does not affect the voltages within the car's ignition system.

Voltage regulation is needed only during periods of standby (receiver) operation, for the voltage applied to the equipment during transmission is within a tolerable range and there is no need for regulation during this period. This lower voltage is due to (1) the decreased voltage at the source under a heavy load, and (2) the greater voltage drop in the cabling to the radio equipment.

When the voltage to the regulator rises above the maximum which can be tolerated, the regulator places a dropping resistor in series with the supply line to the radio, thus lowering the voltage at the equipment to a more suitable value.

Figure 2 shows the regulator circuit and its connection into the primary circuit. Switch S1 represents the contacts of the master relay in trunk-mount units. When the switch on the operator's control head is turned on, this relay closes, completing the path from the battery to the radio equipment. Starting at the upper battery terminal, the path is through the coil of relay C to circuit point "1." Here there are two possible paths. If the contacts of both relays (B and C) are open, the current must go through the .25 ohm resistor and on to the radio. If either relay is operated, however, the resistor will be shunted and the current goes directly to the radio (without going through the resistor).

Operation of the regulator depends upon (1) the voltage applied to the regulator from the battery and (2) the amount of current required by the radio equipment.

Relay C is current sensitive and should operate (contacts close) during transmit, when the current is high; it should release (contacts open) during standby, when the current is low. Thus, the current relay contacts will normally be open for standby and closed for transmission.

When relay C operates, point 1 is connected to point 2. This bypasses the current around the .25 ohm resistor; the path is directly from the battery to the radio.

2. See "Vehicle Battery Voltage Regulation," reference T-9B.

(Only the relay coil with its negligible resistance remains in the path.) Thus, relay C closes during transmission periods and the primary power is applied directly to the radio equipment, regardless of the operation of the other two relays.

During standby operation, the current drain is comparatively low and the current relay contacts remain open. The .25 ohm series resistor may or may not be in the circuit, depending upon the operation of the other two relays (A and B). These are voltage operated relays; they are open or closed according to the voltage applied from the primary source.

Relay B operates with as little as 9 volts applied so its contacts are normally closed as soon as the radio is turned on. If only relay B is energized (not relay A), its contacts shunt the resistor and the primary voltage is applied directly to the equipment.

This condition continues as long as the primary voltage does not exceed a predetermined allowable maximum (13.5 to 14.2 volts). If the voltage exceeds this value, the .25 ohm resistor will have to be in series with the supply in order to lower the voltage at the radio; relay B must be released.

Relay B, it will be noted, is controlled by the normally closed contacts of relay A. If relay A operates, the path to relay B is broken and relay B releases. Thus, when the primary voltage reaches the predetermined value, relay A operates and relay B releases. The .25 ohm resistor is now in the circuit and the voltage at the radio is lowered.

If the applied voltage becomes as low as 12.7 volts and the resistor is allowed to remain in the circuit, the voltage at the radio may be below the minimum value required for good operation. At 12.7 volts (or less), relay A will release. This allows relay B to operate, taking the resistor out of the circuit.

The average mobile units will draw about 7 amperes during standby operation. This current will produce a voltage drop of 1.75 volts across the .25 ohm resistor and the voltage at the filaments is thus reduced to a more satisfactory level.

High-Voltage Considerations — Circuits

All the filaments in the equipment remain on when either the receiver or the transmitter is being operated, but only one of these units (receiver or transmitter) may operate at one time. This is accomplished by switching the plate and screen supply voltages either to the transmitter or to the receiver according to the position of the controlling (transmit-receive) relay. By removing the plate and screen supply voltages from either unit, the amount of power taken from the high voltage section of the supply is kept to a

In Most Mobile Two-Way Radios, the Power Supply is Switched Between the Receiver and Transmitter by the "Push-To-Talk" Button on the Microphone.

minimum. This also provides a convenient method of muting the receiver during transmissions, and of removing the transmitter from the air when receiving.

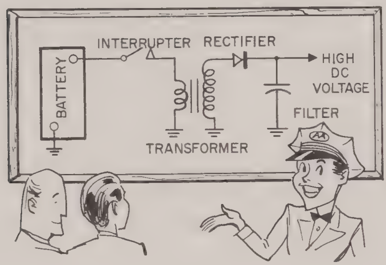
The supply voltages are switched between receiver and transmitter by the contacts of the transmit-receive relay. This basic system is shown in figure 3A. Three secondary windings are used, each with its own rectifier and filter section. Secondaries S1 and S2 furnish the correct voltages for the plates and screens of the tubes in the receiver and transmitter. Secondary S3 furnishes the correct bias voltage for the transmitter.

Secondary S1 provides an output of about 200 volts from its rectifier-filter when "loaded" by the receiver. This voltage is connected to the receiver when the transmit-receive relay is in its release position. This is the only voltage furnished by the supply to the receiver.

In the transmit position, the transmit-receive relay must switch the B+ supply from the receiver to the transmitter. In addition, for transmission purposes, it is necessary to have a higher B supply for the final stages of the transmitter. This is made possible in figure 3A by connecting the DC output of secondaries 1 and 2 in series. Thus, the "B+" is switched from the receiver to the low-voltage stages of the transmitter and, at the same time, other contacts on the relay apply the high "B++" supply to the final stage of the transmitter. As shown in figure 3A, it is common to label the low B supply as "B+" and the high B supply as "B++." The value of the B++ voltage varies with transmitter requirements. For the average mobile transmitter, it is around 400 volts.

Additional control circuitry and other modifications will be found in some power supplies, but figure 3A is typical of systems which are

often encountered in mobile installations. If the power source includes a dynamotor, only one vibrator may be used (or none at all) and the high voltage is furnished by the dynamotor itself -- not by a series arrangement. Dynamotor supplies are discussed in a later assignment.



Vibrator and Transistor Power Supplies Perform Four Functions: Change DC to AC, Step Up the AC, Rectify to DC, Filter the Output.

The circuits of figure 3A are shown in greater detail in figure 3B. The output voltage of secondary S1 is rectified by a full-wave bridge circuit, and a conventional filter provides a smooth DC voltage to the receiver or to the low-voltage stages of the transmitter. A resistor parallel to the output serves to discharge the filter capacitors when the equipment is turned off. This removes the shock hazard associated with charged capacitors.

With the relay in the receive position, the output of S1 is applied to the receiver. The receiver continues to operate as long as this relay stays in the receive position. When the operator presses the "talk" button on his microphone, however, the transmit-receive relay operates, closing the four contacts shown on the diagram. The AC voltage of S2 is applied to two terminals of the full-wave bridge rectifier and the output from the rectifier appears across the other two terminals of the bridge, the "left" side being negative. This terminal is connected to the positive output terminal of S1, so these two outputs are now connected in series.

The B++ voltage at the output terminal of S2 will be the sum of the voltages of S1 and S2. A single output capacitor is sufficient to filter the voltage to the transmitter final. The circuit to the transmitter is completed through a third set of relay contacts. The fourth set of relay contacts switches the "B+" voltage from the receiver to the low voltage stages of the transmitter.

Secondary S3 furnishes the transmitter bias voltage through the single half-wave rectifier and filter capacitor. Little or no power is used in this circuit.

Full-Wave Bridge Rectifier

The operation of the full-wave bridge rectifier may be seen in figure 4. When AC is applied from the transformer secondary to the upper and lower terminals, DC is available at the opposite corners of the bridge. Each half-cycle of applied AC is rectified and appears across the output (load).

When the upper terminal is positive (and the lower terminal of the bridge negative), the current (electron flow) follows the path shown by the solid arrows. The output voltage appears across the load resistor, the "right" end being positive. On the next half-cycle the upper terminal is negative and the lower terminal positive. The current path is now shown by the broken arrows. Again the current through the load makes the right side positive. Thus, the bridge is a full-wave rectifier.

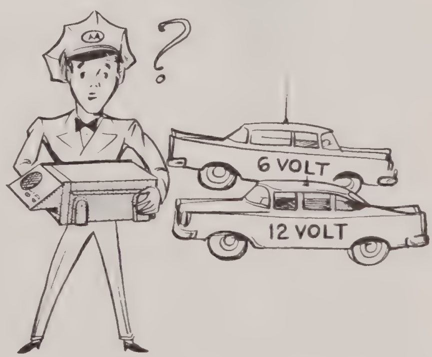
The filter, consisting of a coil and two capacitors, smooths out the pulsations and a relatively steady voltage (pure DC) is made available at the load. The load shown in figure 4 represents the receiver and transmitter circuits.

Multiple Voltage Outputs

The average two-way communications transmitter requires different supply voltages for its several stages. The power amplifier supply should be about 400 volts, the multiplier stages require from 275 to 300 volts, and the oscillator and modulator stages can be operated from the receiver supply voltage. The receiver supply voltage is usually between 180 and 200 volts when receiving, and this voltage could possibly be used for the multiplier stages if it remained constant. It usually drops to around 150 volts, however, under the heavy load of the transmitter. It is, therefore, preferable to use a higher voltage for the multipliers if they are to produce a satisfactory output.

Figure 5A shows a very practical method of providing this voltage for the multiplier stages. By utilizing a tap on the high-voltage section, two DC output voltages are obtained from that section of the supply; one is determined by the voltage of the entire winding (250 volts) and the other is equal to approximately one-half this voltage (125 volts). When these voltages are placed in series with the 150-volt section, the output voltages are 150 volts, 275 volts and 400 volts, respectively. The 275-volt output can then be used for the multiplier stages.

The circuit which makes the 275-volt output possible is shown in figure 5B. The two rectifiers (part of the bridge rectifier circuit) are themselves a full-wave



Many Modern Two-Way Radios are Interchangeable between 6-Volt and 12-Volt Vehicles.

rectifier for the voltage across each half of the winding, and the positive side of the DC output voltage can be taken from the center tap of the winding. This full-wave rectification is shown by the arrows. When the bottom of the winding is negative with respect to the center tap, the current (electron flow) follows the path shown by the solid arrows. The end of the load connected to the center tap is positive. On the next half cycle, the upper terminal of the transformer winding becomes negative with respect to the center tap, and again the current through the load---shown this time by the broken arrows---makes the left terminal of the resistor positive.

Figure 5C shows further details. The action of the rectifiers makes point B of the diagram 125 volts positive compared to point A, and point C is 250 volts positive compared to point A. Point A, however, is already 150 volts positive with respect to ground because of its connection to the positive side of the 150 volt supply. Compared to ground, then, point B is "plus 275 volts" and C is "plus 400 volts." (The manner in which a full-wave bridge produces 250 volts between C and A has been explained in connection with figure 4.)

The filter sections have been omitted from figure 5C for simplicity; these filters are the usual LC circuits found in any conventional power supply.

Types of High-Voltage Rectifiers

The "dry" type of rectifier has almost completely replaced vacuum-tube rectifiers in mobile two-way communications equipment. There are several reasons for this as we shall soon see. First, however, let us examine the various kinds of dry rectifiers being used in mobile equipment today.

Selenium rectifiers were the first type to be substituted for the vacuum tube. Each cell, composed of one positive and one negative plate, will withstand only about 40 volts across its terminals, but by connecting cells in series almost any voltage rating can be attained. The current capability depends to a great extent upon the rectifying surface and heat dissipation ability of the cells; units having a capacity of 500 ma are practical as to both size and cost. The selenium rectifier has thus proved very satisfactory in the mobile power supply. Selenium rectifiers belong to a class known as "dry disc" rectifiers.

A more recent substitute for the vacuum tube rectifier is the silicon diode, which belongs to the semiconductor family. With more economical manufacturing methods, silicon diodes will likely replace all rectifiers in use today, in mobile equipment.

The main limitations of the vacuum-tube rectifier are (1) its

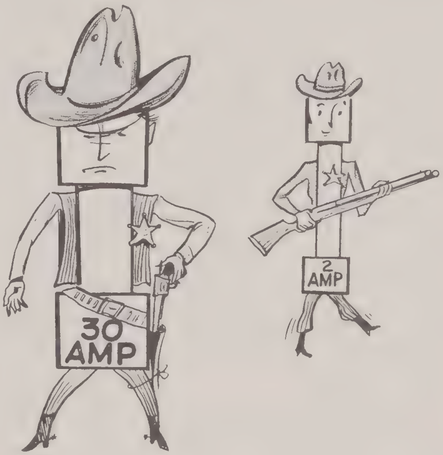
fragility and (2) its consumption of filament power, which results in higher operating temperatures and less efficiency. Selenium and silicon rectifiers are not subject to these limitations; neither requires filament power, and both are comparatively rugged, withstanding considerable vibration and shock.

Selenium and silicon rectifiers are also more reliable than the vacuum type, for they have a much longer useful life. Since selenium and silicon rectifiers have less internal voltage drop than found in vacuum tubes, these rectifiers can be used with transformers having lower secondary voltages to produce the same output. The silicon rectifier is superior to the selenium in this respect, providing about 10 percent more output voltage for the same input voltage.

The symbol used to represent a dry rectifier differs from that used for vacuum tubes, but there is no way to tell from the schematic whether it is selenium or silicon; the same symbol is used for both.

Regulating the B Supply

Without some means of controlling the voltages applied to radio equipment, damage may take place. The need for regulating the primary voltage of the 12-volt ignition system was pointed out earlier in this lesson. Regulation of the B supply voltage is also sometimes incorporated in two-way equipment, but for a different purpose.



Fuses of Varying Size and Ratings "Protect" Both the Mobile Radio and the Electrical System.

If the plate and screen supply to the high-frequency oscillator varies appreciably, for example, the oscillator will change frequency. Where the oscillator operates at a high frequency or where a high multiplication of the oscillator frequency takes place, even a slight variation of frequency (due to changes in supply voltage) can impair the operation of the equipment. Thus, it is common to find that 450-mc equipment incorporates some means of regulating the B supply to the oscillator. With recent refinements in oscillator circuitry, successful operation of this equipment has become possible by using regulation of the oscillator supply voltage alone (without including automatic frequency control).

Although more elaborate methods of voltage regulation can be used, a system making use of a gas-filled diode regulator tube is the most practical for mobile equipment. It is light, compact and relatively inexpensive, and it satisfies the regulation requirements of the oscillator.

The regulator tube keeps the load voltage constant regardless of changes either in the load current or in the supply voltage. This action depends upon the ability of the regulator tube to maintain a constant voltage over a wide current range.

Shown in figure 6A, the regulator tube is placed parallel with the load, so that the voltage across the tube is the voltage applied to the load. Between the load and the supply voltage (which must always be higher than the load voltage) a series resistor provides a voltage drop which is always equal to the difference between the supply voltage and the load voltage.

When the supply voltage increases, the voltage at the regulator tube also starts to increase. The tube now conducts more current, however, producing a greater drop across the resistor and maintaining a constant load voltage. If the supply voltage should decrease, the regulator tube voltage will also start to decrease. The tube current then decreases and lowers the voltage drop across the resistor. This keeps the load voltage constant.

The operation of the regulator tube for changes of load current follows the same basic idea. Increases of load current tend to increase the drop across the resistor, thereby lowering the load voltage. The regulator tube, however, conducts less and maintains a constant resistor current and load voltage. Decreases of load current tend to increase the load voltage (due to the lower drop across the resistor), but the tube conducts more current and again the load voltage is stabilized.

Various voltages can be had with this system, depending upon the voltage across the regulator tube. Regulator voltages are rated accordingly, the most common being 105 and 150 volts. Where higher voltages are desired, two or more regulator tubes may be connected in series. The load voltage is then the sum of the voltage ratings of the separate tubes. The arrangement is shown in Figure 6B.[3]

The VR (voltage regulator) tube was first used by Motorola in their 450-mc receivers. In this application, the plate and screen supply voltages to the oscillator are maintained constant for improved frequency stability. In transmitters, the screen supply of the first multiplier is sometimes taken from the same regulated source. Where this is the case, a more constant load is maintained on the modulator, resulting in greater modulation linearity.

3. See TM11-662, pages 193-194.

STUDENT NOTES

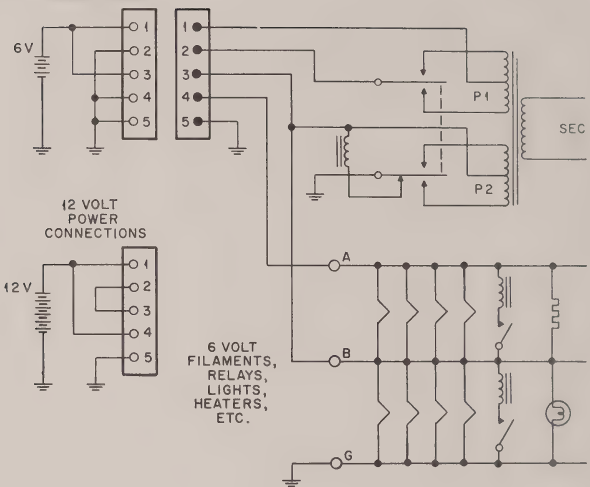
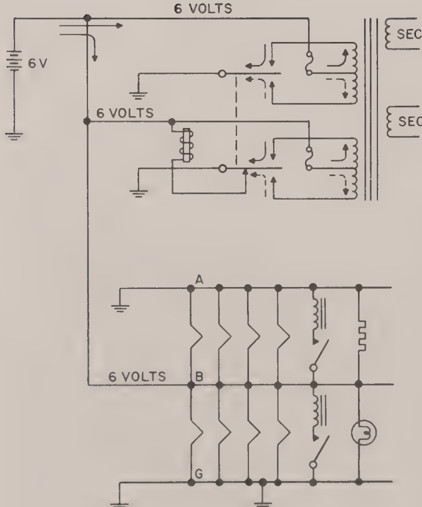
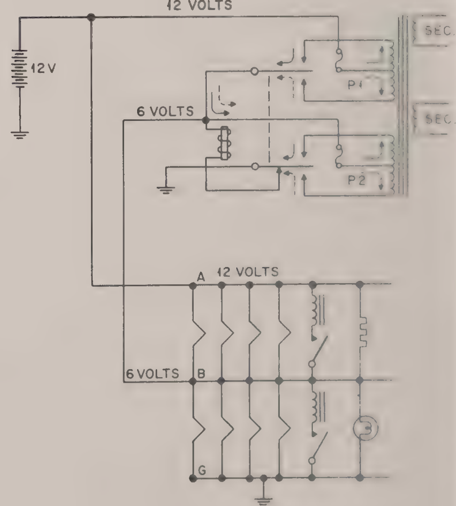


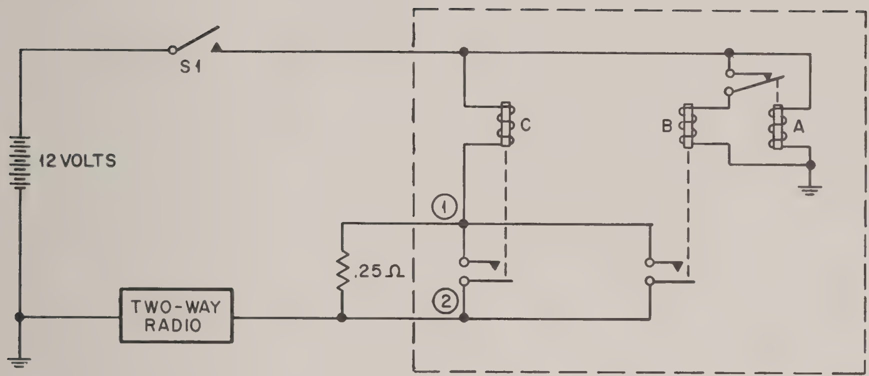
FIGURE 1A



6-VOLT OPERATION
FIGURE 1B



12-VOLT OPERATION
FIGURE 1C



12-VOLT REGULATOR
FIGURE 2

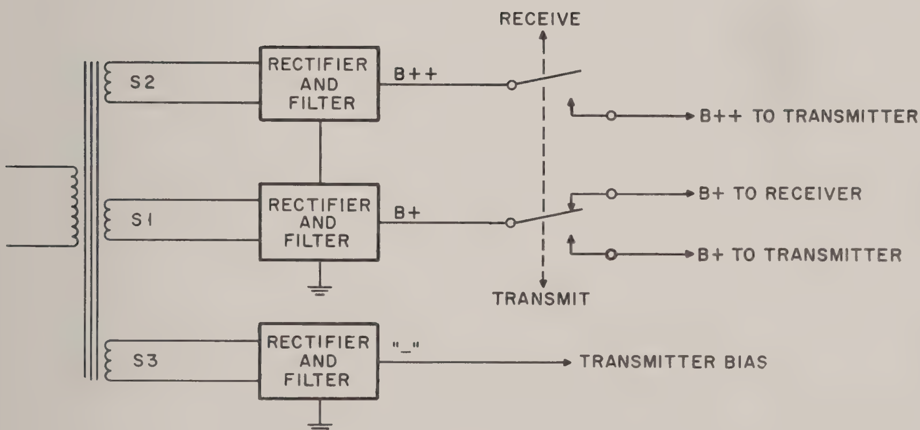


FIGURE 3A

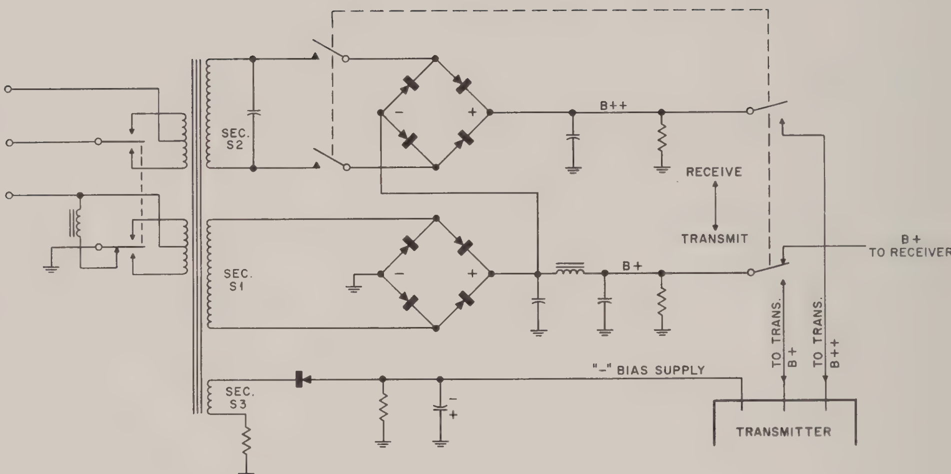
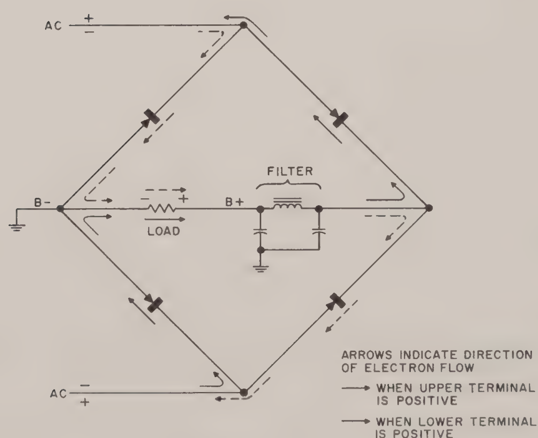


FIGURE 3B



FULL-WAVE BRIDGE RECTIFIER
FIGURE 4

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STUDENT NOTES

STUDENT NOTES

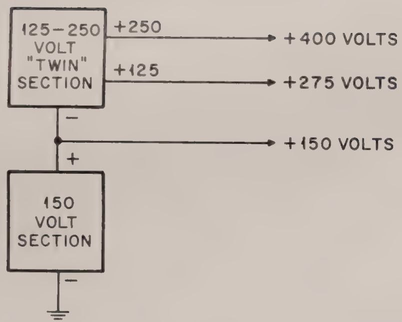

FIGURE 5A

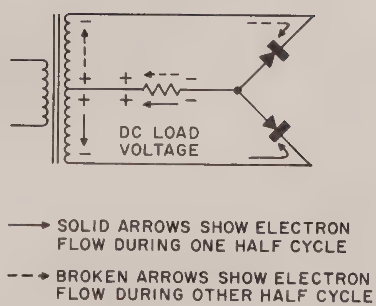

FIGURE 5B

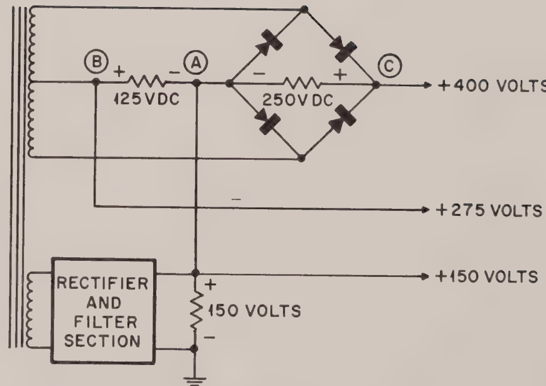

FIGURE 5C

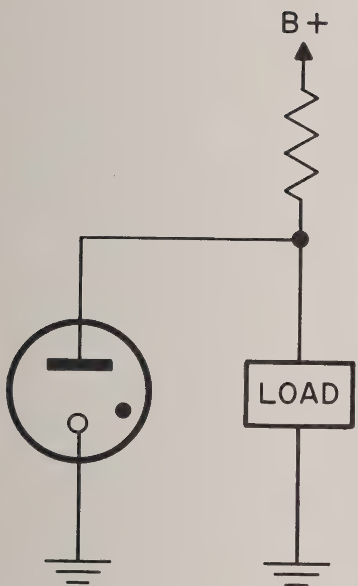

FIGURE 6A

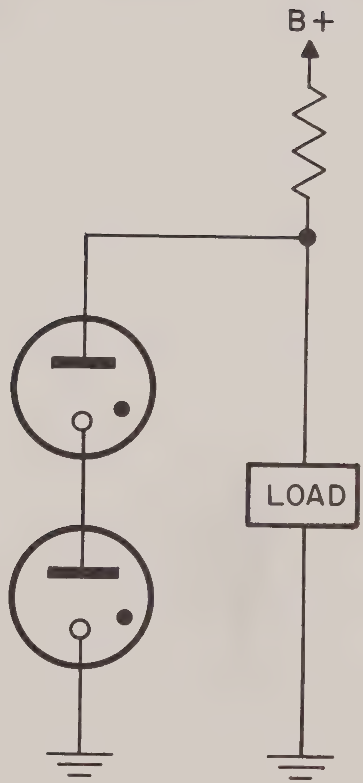

FIGURE 6B

B SUPPLY
VOLTAGE REGULATION

national

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LESSON TA-10
POWER SUPPLIES

Vibrator and Dynamotor Supplies

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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-10
POWER SUPPLIES

Vibrator and Dynamotor Supplies

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

VIBRATOR AND DYNAMOTOR SUPPLIES

LESSON TA-10

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Large state recreation areas deploy their forces for maximum protection of the public at all times. Here a lifeguard uses radio to arrange his schedule so that a beach in heavy use is adequately protected.

VIBRATOR AND DYNAMOTOR SUPPLIES

Lesson TA-10

Introduction

In this lesson, we shall study vibrator and dynamotor power supplies. Two types of supplies are used. One has a vibrator only, while the other includes both a vibrator and a dynamotor. We refer to the latter as a dynamotor supply. In this power supply, the dynamotor furnishes the high voltage for the final transmitter stages, while the vibrator supplies the other transmitter (and receiver) voltages. For some dynamotor supplies, the dynamotor supplies all the transmitter voltage and the vibrator supply is used exclusively by the receiver.

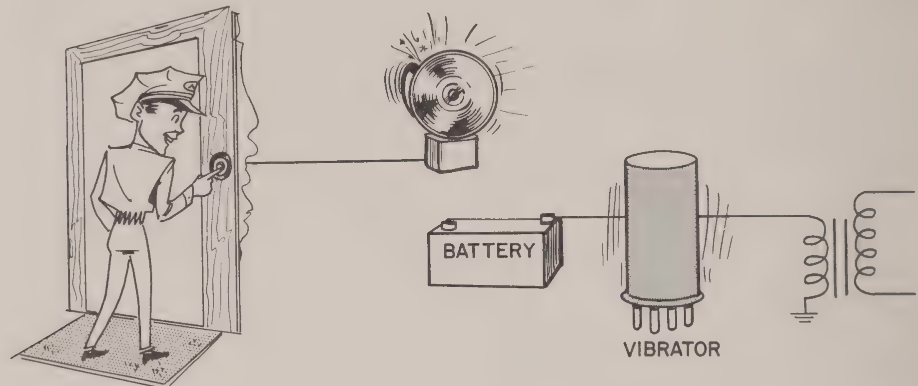
In addition to studying the basic principles of both the vibrator and the dynamotor, we shall analyze the circuitry of each type of supply and discuss practical service procedures.

Operation of the Vibrator

Fundamentally, the vibrator acts as an interrupter of the primary DC current, and is often referred to as an interrupter. This interrupting action, coupled with a reversing of the current through the primary of a transformer, creates an alternating voltage that can be transformed (amplified) the same as any other AC voltage.

Figure 1A represents a conventional power supply in which AC is (1) applied to the transformer primary, (2) stepped up to the required AC voltage in the secondary and (3) rectified to DC. This circuit requires an AC source for proper operation. Figure 1B shows an arrangement which can be used to produce the required AC in the primary from a DC source. With the switch to the right, the direction of current (electron flow) through the primary is shown by the solid arrows. When the switch is to the left, the current through the primary is in the opposite direction (shown by the dotted arrows). An alternating current is thus produced in the primary winding.

Another arrangement to produce the same effect is shown in figure 1C. Here we use a center-tapped primary winding and a single-pole, double-throw switch. With the switch in the up position, the direction of the current (electron flow) is "up" through the upper half of the primary (solid arrows); with the switch in the down position, the direction of the current is "down" through the lower half



The Basic Principle of Operation of the Vibrator is the Same as That of the Doorbell; the Only Difference is in the Application.

of the winding (dotted arrows). The action of the vibrator in figure 1D is similar to that of the switch in figure 1C.

Vibrator operation is brought about by the action of its drive coil and drive coil contacts. The drive coil causes the armature to move, which, in turn, closes one pair of main vibrator contacts and establishes current in 1/2 the primary of the transformer. At the same time, it opens the driver contacts in series with the drive coil which allows the armature to spring back. Inertia of the armature causes it to close the opposite pair of main contacts and also the driver contacts. This reenergizes the coil and the armature swings back and forth between the contacts, as in a doorbell buzzer, providing the desired switching action.

Thus, as the armature alternately completes the circuit to the two halves of the primary, the current path is first through one half of the winding and then through the other half.

Vibrator Waveform and the Buffer Capacitor

The current through the primary winding, as a result of the vibrator action, will produce a voltage drop across the primary winding which will resemble the waveform of figure 2. Times T1 and T2 represent the time during which the vibrator contacts are closed and current is flowing respectively through each half of the primary winding. The in-between periods of figure 2 represent the "open" time, or the time elapsed during the travel of the reed from one contact to the other. The ratio of the closed time to the open time is normally referred to as the time efficiency of the vibrator.

Figure 2 is the ideal waveform and is not encountered in actual practice. This is primarily true because of the inductance of the transformer windings. The sudden making and breaking of the current path through the transformer primary causes current transients and high induced voltages. Without

some correction of this condition severe arcing will occur at the vibrator contacts and will prematurely limit the useful life of the vibrator. Also, these high induced voltages could produce a breakdown in the transformer insulation.

Here is where the buffer capacitor is of great importance. Used in conjunction with the inductance of one of the windings, the capacitor tunes that winding to a frequency slightly higher than the vibrator frequency. This tends to bring the voltage across the vibrator contacts to zero potential at the time the contacts close. The capacitance of the buffer, then, is determined by the inductance of the winding and the timing characteristic of the vibrator.

In figure 3, the dashed line indicates the natural resonant characteristic of the tuned circuit (the buffer and the transformer winding) in relationship to the vibrator waveform. Where the buffer capacitor is used across the primary winding its voltage rating may be low, but a large capacitance is required, for the primary inductance is ordinarily very small. The high-voltage secondary has a larger inductance and allows for a smaller capacitance. The voltage is relatively high, however, and the voltage rating of the capacitance is usually 1600 volts or higher.

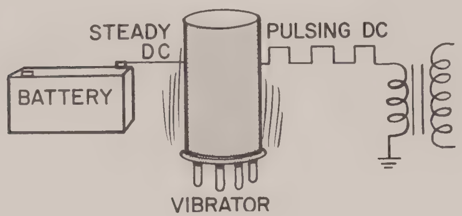
Buffer capacitors connected across the secondary winding seem to be the most practicable and are found in most equipment. In replacing a defective buffer capacitor, the serviceman must use a unit having the correct capacitance and a sufficient voltage rating. Otherwise, the vibrator life may be shortened.

The Synchronous Vibrator

The synchronous vibrator, shown in figure 4, was at one time used rather extensively. A second pair of contacts to the vibrating reed rectify the secondary transformer voltage, thereby eliminating the high-voltage rectifiers.

The rectifying contacts alternately complete the circuit to each half of the secondary winding. When the armature moves up, the center-tap of the secondary must be positive with respect to the upper terminal of the winding. If the polarity of the induced secondary voltage is reversed, the output voltage will be negative (compared to ground) instead of positive. The remedy for this condition is to reverse the connections either to the primary or to the secondary winding.

The synchronous vibrator requires frequent replacement, particularly where the load is heavy, and replacement synchronous vibrators are more expensive. For these reasons, modern vibrator power supplies for mobile communications equipment use either silicon or selenium high voltage rectifiers, separate from the vibrator function. The rectifiers are reliable and seldom required replacement.



The Vibrator Changes DC from the Battery Into a Square Wave Pattern at the Transformer Primary.

The Complete Vibrator Power Supply

The complete schematic of a typical vibrator power supply appears in figure 5. This supply is designed for front-mounted, 10 watt mobile stations. During standby (receive position), the supply delivers 190-200 volts DC at 70 ma. When transmitting, the supply furnishes 140 volts DC at 15 ma, 270 volts DC at 40 ma, 335 volts DC at 120 ma and 17 volts DC for bias.

Primary power requirements are 11.0 amps on standby and 24.5 amps on transmit when operated from 6.3 volts; 5.8 amps on standby and 13.5 amps on transmit when operating from a 12.6-volt source. Two 15 ampere fuses in the primary leads furnish protection from shorts or defective parts.

In the primary circuit, capacitors C3, C5 and C6 together with resistors R3, R4, R5 and R6 serve as filters for reducing hash. The coil L1 and capacitors C1 and C2 function as a filter in the receiver 6-volt filament supply line, and capacitors C11, C12 and C13 are used as filters in the supply lines leading to the transmitter.

Capacitor C4 in the upper secondary winding serves as the buffer capacitor, discussed previously in this lesson. The buffer has a voltage rating of 1600 volts. The three secondary windings correspond to the basic system discussed in the preceding lesson. The middle secondary is used as the basic B supply source, being rectified and filtered to the required DC by the bridge rectifier (CR5,6, 7,8) and filter L2 and C8. Resistor R8 is a bleeder to discharge the capacitors when the power is turned off.

The output voltage of the B supply (about 200 volts) is switched between the receiver and the transmitter by the transmit-receive relay, K1. This relay is normally de-energized, or in its "released position." When the operator wishes to transmit, the relay is energized by pressing the "press-to-talk" button on the mike. With the relay in standby position, the B supply voltage is connected to the receiver through relay contacts 9 and 10. With the relay in transmit position, this B supply voltage is fed to transmitter terminals 6 and 9 (for screen and oscillator supply). Because of the heavier drain on the supply by the transmitter circuits, this B+ voltage is about 140 volts during transmit. The microphone voltage is also derived from this voltage. The correct value is obtained from voltage divider resistors R9 and R12.

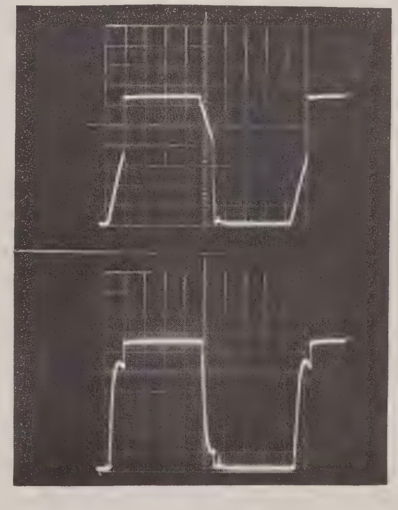
The B supply voltage is protected by pilot lamp I-1 acting as a fuse. Any overload will cause the pilot lamp to burn out, preventing damage to the rectifiers or other components as a result of excessive current. It is thus important to use the correct pilot light; too low a current rating will cause numerous and unnecessary burnouts, while too high a current rating may not afford adequate protection.

The high voltage required for transmitter operation (commonly referred to as B++) is obtained by connecting the output of the upper secondary circuit in series with the receiver B supply. The connection at the left of the rectifier bridge is returned to the positive side of the receiver B supply. This places the two rectifier sections in series and the resulting voltage is the sum of the voltages of the two sections. This high (B++) voltage is available only when the relay is in transmit position. The path from the secondary winding to the bridge rectifier is completed through relay contacts 5 and 6, and the high voltage output is made available at the transmitter through relay contacts 7 and 8. At the same time, the low voltage output (B +) is applied to the transmitter through relay contacts 10 and 11.

There is about 335 volts at terminal 10 of the transmitter and the lower B supply is about 140 volts. This means that the upper transformer section produces a DC output of nearly 200 volts. This output voltage is filtered by capacitor C8A. Resistor R2 discharges the capacitors when the high voltage is discontinued.

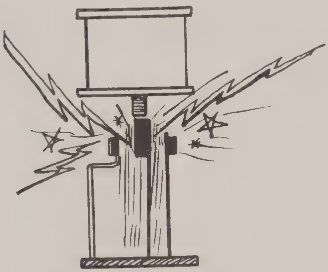
In the high voltage (B ++) supply line to the transmitter, we find the two parallel resistors R10 and R11. These resistors lower the voltage supply to the plates of the multiplier stages of the transmitter, about 270 volts under normal operation.

The lowest secondary winding on the transformer supplies the bias voltage required by the power stages of the transmitter. We have already spoken of the fixed bias on the grids of the transmitter, and it is the purpose of this transformer winding, plus the rectifier and filter, to furnish such a voltage.

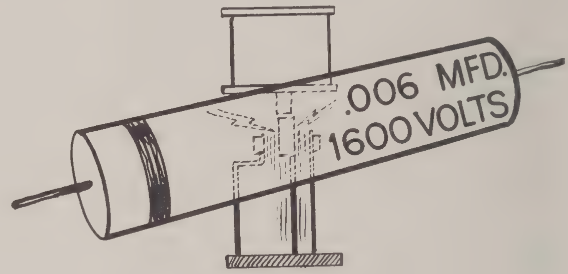


Typical Voltage Waveforms at the Secondary of the Vibrator Transformer: Upper, With the Buffer Capacitor Installed; Below, Without the Buffer.

The rectifier is connected so as to produce a negative output voltage, and capacitor C7 supplies the necessary filtering action. Resistor R7 serves as a current limiting device and R13 is used to stabilize the voltage and to complete the DC return path for the grid circuits of the tubes. The 17-volt bias voltage is present at all times. It is used for biasing purposes only, and, there is almost no load current.



VIBRATOR



VIBRATOR

Besides "Tuning" the Circuit, the Buffer Capacitor Greatly Attenuates the Noise Pulses Otherwise Present in the Vibrator Power Supply.

Terminals 1 and 2 of relay R1 are connected to the relay energizing coil. Terminal 2 is connected directly to the ungrounded side of the 6-volt supply, and the relay is energized by completing the ground connection to terminal 1. This ground is not shown on the diagram, but the path is through the wire leading to terminal 15 on the transmitter connector, and the ground is normally established by depressing the "press-to-talk" button on the operators microphone.

The transmit-receive relay provides still another function. Contacts 3 and 4 of the relay, closed in the transmit position, energize the antenna relay which also operates on 6 volts. The antenna relay transfers the antenna from the receiver to the transmitter. One terminal of the antenna relay is already grounded. Then, when the transmit-receive relay is energized, the circuit to the antenna relay is completed through contacts 3 and 4.

Advantages of the Vibrator Supply

It is convenient, when discussing the advantages of the vibrator supply, to compare it with the dynamotor supply, also discussed in this lesson. The following advantages of the vibrator supply distinguish it from the dynamotor supply; light weight, small size, higher efficiency, quiet operation, lighter cabling, no surge of starting current, not affected by atmospheric conditions, simple and economical service and replacement.

With our study of the vibrator supply completed, we are now

ready to discuss the dynamotor type of power supply.

Dynamotor Operation

The dynamotor is essentially a generator and a motor, and is used for changing a low DC voltage to a higher DC voltage.

It is a single unit having a double armature winding, both of which are wound on the same core, but connected to separate commutators. One winding serves for the driving motor when energized from a low DC source. The other winding generates a high voltage when rotated within the magnetic field, and the output voltage is taken from this winding. A single field winding is used to provide the magnetic field for both driving and generating purposes. See figure 6.

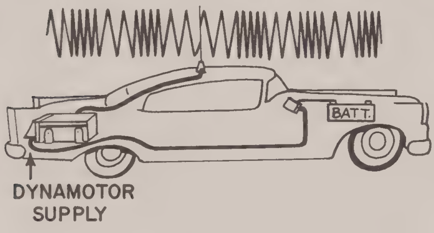
Current from the battery flows through the field coils and through the motor winding of the armature, setting up a magnetic field around both. (Heavy lines are used to indicate the low-voltage armature circuit.) The magnetic fields cause the armature to rotate. Since the motor armature and field windings are in parallel, this is called a shunt-wound motor. It is a characteristic of this type of winding that the speed of the motor remains fairly constant with changes in the load.

In addition to the shunt type of field winding, it is common to include a small series - wound field (not shown in figure 6) for fast starting. The starting current flowing through this winding produces a strong field and thus a high starting torque. The dynamotor thus reaches its operating speed in a short time and makes the high-voltage available for transmitter operation as soon as the operator wishes to send his message---there is no delay while the high voltage is being made available. Without the series field, the dynamotor would be considerably slower in starting and the operator would have to postpone his message for a few seconds after pushing the "press-to-talk" button.

The high-voltage armature winding, represented by the lighter lines, is wound on the same armature. It rotates with the motor winding and cuts the magnetic field, generating a voltage which appears at the high voltage commutator. The output voltage is determined by (1) the number of turns in the high-voltage winding, (2) the strength of the field and (3) the speed of rotation.

A certain sparking occurs between the brushes and commutators as the circuit to each bar of the commutator is broken. To prevent interference from these high-frequency currents, filters are placed in both the input and the output of the dynamotor. These filters are shown in figure 6. There are fewer segments on the input commutator and the switching occurs at a lower frequency, but the current is also considerably greater. The primary circuit thus requires heavier filtering than the secondary.

Another reason for keeping the primary voltage free from any ripple, is that it is used for the tube filaments, and any high-frequency component can produce undesirable noise fluctuations in the tube currents. Modern dynamotors are relatively free from noise due to arcing, and a suitable capacitor is usually all that is required for filtering the high-frequency component from the output.



The Dynamotor Power Supply Has Been Used Extensively in Mobile Installations of High Transmitter Power and Heavy Duty Cycle.

A schematic symbol representing the dynamotor is shown in figure 7A. The field is not shown, and two circles represent the motor and generator windings of the armature. For 6/12 volt operation, a dynamotor has been developed which has two motor windings, each operating at 6 volts. The two primary inputs may be operated in parallel for a 6-volt source (figure 7B), or in series for a 12-volt source (figure 7C). This will be taken up at greater length when we discuss the complete dynamotor power supply.

Dynamotors built for 6/12-volt operation have separate fields, one for each motor winding. This makes it possible to connect the two motor systems either in parallel for 6-volt operation or in series for 12-volt operation.

Certain dynamotors have two high-voltage windings, completely independent of each other (figure 7D). The outputs have separate commutators and separate brushes, and these may be connected as desired. The series connection is used to provide a higher voltage. This arrangement has the advantage that the individual generator windings do not develop as high a voltage as would be required for a unit having but one winding, thus minimizing the possibility of breakdown between the windings. Several Motorola power supplies utilize this type of dynamotor construction.

A reversal of the battery voltage has no effect on the operation of vibrator supplies, but the same cannot be said of the dynamotor supply. In the case of the dynamotor, the output voltage will be reversed whenever the primary polarity is reversed. The dynamotor will continue to rotate in the same direction, for the polarity of the field and armature windings both are reversed. The generator winding, however, will be cutting a magnetic field of the opposite direction; hence the output voltage will be reversed in polarity. Since either the positive or the negative side of the battery may be grounded in cars, all dynamotor power supplies must incorporate

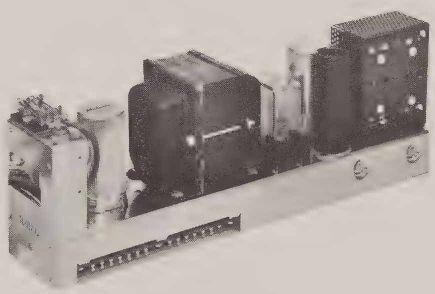
some means for reversing the polarity of the high-voltage output.[1]

The Complete Dynamotor Supply

Figure 8 shows a complete vibrator dynamotor power supply used in a typical Motorola communications receiver and transmitter. With an RF output of 50-60 watts from the transmitter, this unit is intended for a high duty cycle---the transmitter will be operated frequently. A vibrator supply furnishes all the power for the receiver; the dynamotor is not operated until the operator presses the "push-to-talk" button.

The operation of the vibrator during standby operation is similar to that already described for the receiver section of figure 5 and the primary circuit is the same, as far as the 6/12 input circuitry is concerned. All primary voltages are indicated on figure 8 (where two values are indicated; the first is for 12-volt operation and the second is for 6-volt operation). The secondary is also the same; with relay K1 in its release position, the 200-volt output from the bridge rectifier is applied to the receiver. The main difference between figure 8 and figure 5 has to do with the operation of the equipment during transmission.

The two dynamotor relays K2 and K3 are energized through the K1 relay, contacts 6-7 and 11-12, applying 6 volts from the primary source to each of the motor windings. The upper motor winding is supplied through pins 3 and 6 of the power plug J1. For 12-volt operation, these pins are connected to the 6- and 12-volt terminals, respectively. For 6-volt operation, they are connected to 6 volts and to ground. In either case the upper motor winding has 6 volts applied. The lower motor winding is also supplied with 6 volts. One side of the winding is grounded; the other is connected to the 6-volt supply through contacts 3 and 4 on relay K2.



A Typical Motorola Vibrator Power Supply which Operates both the Receiver and Transmitter of the Mobile Two-Way Radio.

In order to place the transmitter in operation, the transmit-receive relay K1 must be energized, by grounding coil terminal 1. This is accomplished through pin 9 of the transmitter plug (P1), or by a connection to the control panel (not shown in figure 8). The B supply voltage from the vibrator section is normally applied to the receiver through relay contacts 8 and 9, but this circuit is broken when the relay is energized, and the plate supply lead from the receiver is grounded through R6. This

1. See TM11-681, pages 144-160.

makes the receiver inoperative, at the same time providing a means of discharging the capacitors in the receiver.

The output of this particular dynamotor is about 625 volts, and this is used for transmitter operation. The high DC voltage, provided by the generator winding, is available at the two output pins, which are connected to terminal board J4 so that the upper terminal is positive. This (positive) terminal is connected directly to pin 8 of P1, the transmitter plug. The .8 microfarad capacitor C4 is a ripple filter. The high voltage is lowered to 250 volts by R8 and R9 for application to the low power stages of the transmitter (through pin 4 of the transmitter plug P1). The ground return to the high-voltage supply is through a 75-ohm resistor (R10), producing a negative fixed bias voltage of about 25 volts for the transmitter. The return circuit to the negative side of the high-voltage supply is through contacts 4 and 5 of the transmit-receive relay.

Contacts 3, 4 and 5 of the transmit-receive relay serve to disable the transmitter when not in use. During periods of transmission, the negative return of the high-voltage supply is completed through contacts 4 and 5. In the standby position however, the plate circuits of the transmitter (which are connected to contact 3 of the relay) are grounded through pin 4 and the 75-ohm bias resistor. This means the RF is cut off as soon as the button is released. Otherwise, B+ is present as long as the dynamotor rotates---the carrier dies out gradually. The total dynamotor current passes through the 75-ohm resistor R10, and that the "upper" terminal of this resistor (as seen on the schematic) is negative with respect to ground. The resulting voltage drop across R10 thus becomes a source of fixed bias for the power stages of the transmitter.

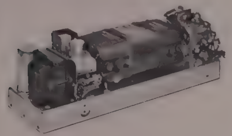
The arrangement of figure 8 uses the vibrator section of the supply exclusively for the receiver, and the dynamotor is used for all transmitter stages. Other dynamotor-vibrator supplies may be different in that the vibrator section may also be used to operate the low-powered stages of the transmitter, (the oscillator, modulator and audio stages in particular).

Dynamotor Maintenance

Due to improvements in the construction of modern dynamotors, little field maintenance is required. By the same token, there is little that the electronic serviceman can do if trouble should develop. In almost all cases it is wise to return a dynamotor to the factory for expert service by trained men who have the experience and tools to do the job right.

The bearings of most dynamotors are sealed and require no lubrication. About the only thing that the technician must do is to keep the unit clean and to replace

the brushes when they become worn. The brushes in Motorola power supply dynamotors are designed to operate for about 100,000 ten-second duty cycles, which means that in average use, the brushes will not require "looking at" for nearly two years.



This Dynamotor Power Supply Includes Both a Dynamotor for Transmitter Operation and a Vibrator for Receiver Operation.

If brushes are left in the dynamotor for too long a time, they become very short and the spring tension slackens. This causes arcing at the commutator. The brushes have a "Line-O-Life" mark to indicate maximum allowed brush wear. When they reach this point, the brushes must be replaced for maximum efficiency and performance. Replacement brushes must be of an approved type. In replacing brushes, care should be taken to prevent fraying the pigtail, or brush shunt. The shunt should have a slight twist, to prevent the fine strands from becoming damaged by the coil springs. If a brush does not fit the brushholder, move it up and down several times in the holder and any small burrs will be removed. Never file the brush to fit the holder!

Accumulated brush dust lowers the resistance of the insulation tubing on the brushholder. This metallic dust should always be blown free from the frame; use an air hose having a 50 to 75 lb. pressure.

Advantages of the Dynamotor Power Supply

Compared to the vibrator type of power supply, the dynamotor offers several marked advantages, especially in the case of equipment having high power outputs or having a high expected duty cycle. Chief among these are the following: longer life without service or replacement, less filtering required and lower RF noise level.

There are a number of disadvantages of the dynamotor, however, compared to the vibrator type of power supply. Specifically they can be listed as follows: heavy, bulky, more expensive, lower efficiency, has a characteristic "whine," high in rush current, requires power relays, more sensitive to dust, and they require service of skilled technicians (for overhaul).

This completes our discussion of the vibrator and dynamotor types of power supplies. In our next assignment--the last in this series about the power supply--we shall study AC and transistorized supplies.

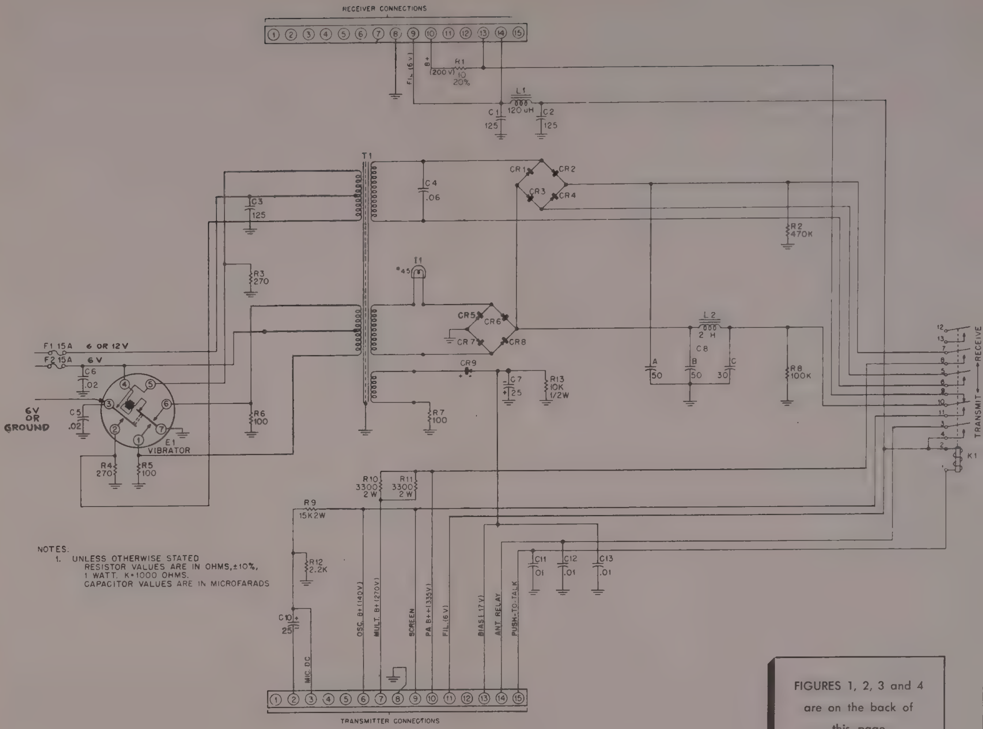


FIGURE 5

FIGURES 1, 2, 3 and 4 are on the back of this page

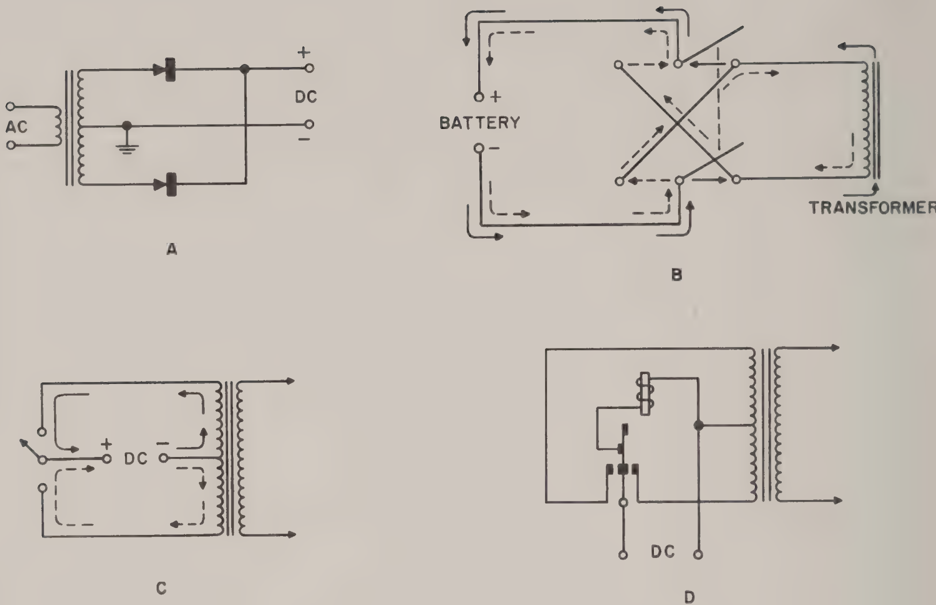


FIGURE 1

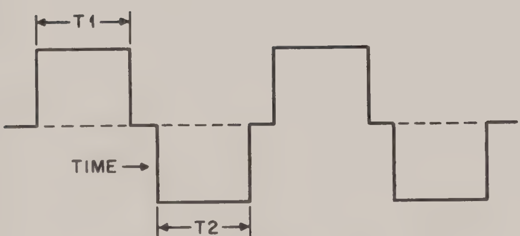


FIGURE 2

FIGURE 3

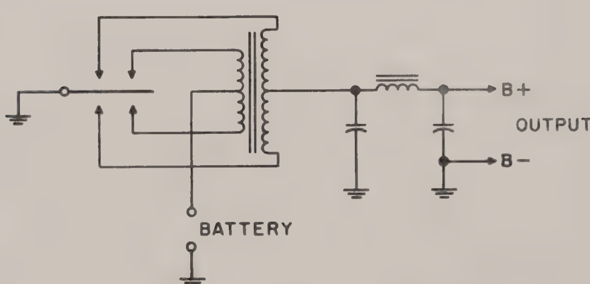
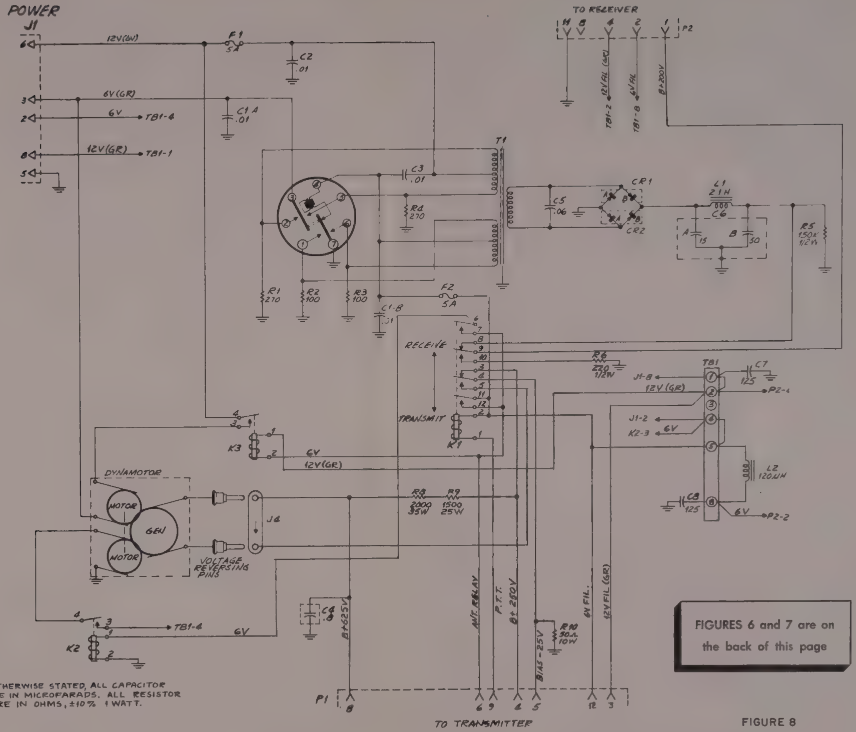


FIGURE 4

STUDENT NOTES

STUDENT NOTES

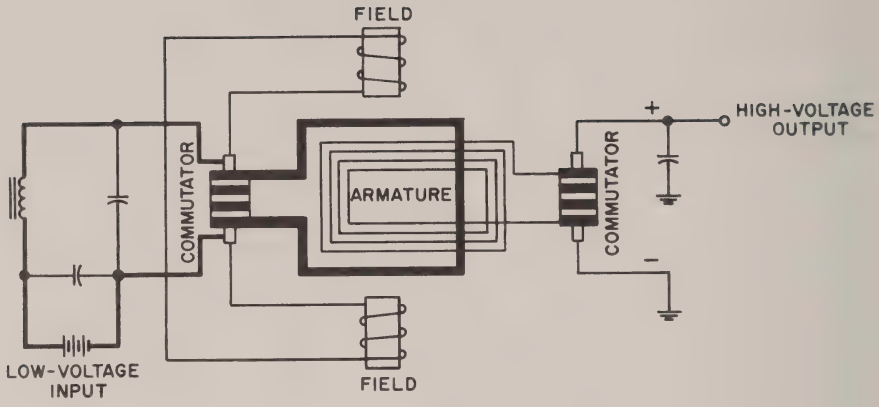
STUDENT NOTES



NOTES:
1. UNLESS OTHERWISE STATED, ALL CAPACITOR VALUES ARE IN MICROFARADS. ALL RESISTOR VALUES ARE IN OHMS, ±10% 1 WATT.

FIGURES 6 and 7 are on the back of this page

FIGURE 8



OPERATION OF A DYNAMOTER
FIGURE 6

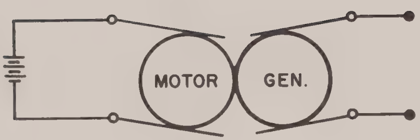


FIGURE 7A

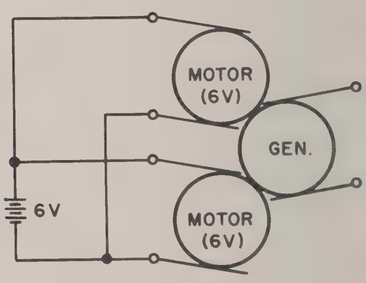


FIGURE 7B

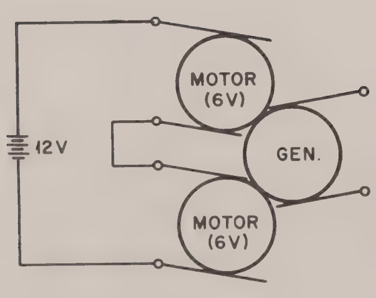


FIGURE 7C

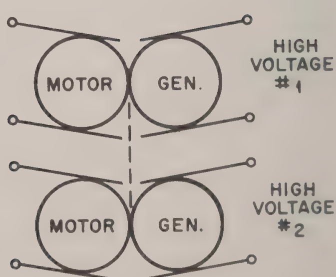


FIGURE 7D

national

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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-11
POWER SUPPLIES

Transistor Switch and AC Power Supplies

MOTOROLA TRAINING INSTITUTE

LESSON TA-11
POWER SUPPLIES

Transistor Switch and AC Power Supplies

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

TRANSISTOR AND AC POWER SUPPLIES

LESSON TA-11

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Two-way radio figures prominently in a highway department's efforts to keep roads open in severe weather. Many departments set up special dispatch centers for use during snow storms.

TRANSISTOR AND AC POWER SUPPLIES

Lesson TA-11

Introduction

This is the last lesson concerned directly with power supplies. This lesson deals with two types of power supplies, one of which is perhaps the most simple and oldest, while the other is probably the newest. The AC power supply has been in use for many years. The transistor, on the other hand, is new not only to its application in power supplies but to the electronic art in general.

Let us start this lesson by talking about the transistor and, specifically, the advantages it offers when used in a power supply.

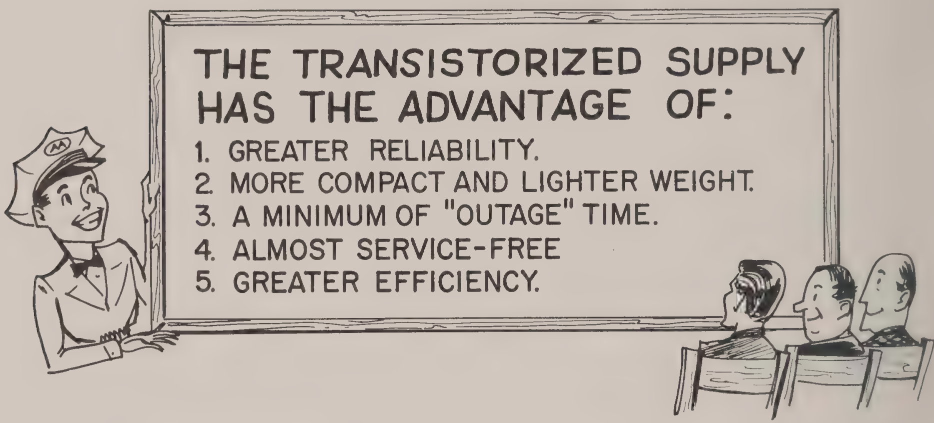
Advantages of the Transistorized Supply

The transistor (actually, a pair of transistors) is used to replace the vibrator in the mobile power supply. Therefore, in stating the advantages of the transistorized supply, comparison must be made with the vibrator type of supply. The first and obvious advantage of the transistorized supply is in its relatively long life. The transistorized supply can give more trouble-free operation with a minimum of "out" time.

Though their present cost is high, it is probable that future transistor supplies will be just as economical or even less expensive than vibrator ones. Because the transistor switch operates at a much higher frequency than the vibrator, the transformers and chokes used in the transistorized supply are smaller and lighter. The efficiency of the transistorized supply is greater than that of its vibrator counterpart. Also, there are no moving contacts to arc and wear.

Unfortunately, transistors have disadvantages along with their advantages. Heat is perhaps the greatest problem encountered in operating the transistor. Besides the normal decline in the efficiency of the transistor when it becomes heated, there is the problem of complete breakdown if the heat becomes excessive. Thus, heat radiators or "sinks" are used to maintain transistor temperatures within an allowable range.

Aluminum heat sinks having several "fins" make practical heat conductors. Due to the high temperature inside of "tube" sets, these must be mounted on the outside of the equipment so that the heat is free to radiate into the surrounding air.



In Addition to these Important Advantages, Over a Period of Time the Transistorized Supply is Probably More Economical.

Basic Idea of the Transistor

The transistor is a semiconductor device that may be used in many applications for which vacuum tubes are used. Because there is some similarity in their operation, it is permissible to make a comparison between the elements of the transistor and those of the vacuum tube.

Figure 1 shows a schematic representation of the transistor. The emitter acts like the cathode of a tube---it is the source from which the current of the transistor is established. The base is somewhat like the grid of a tube in its action; the collector is the output and is similar to a tube plate.

Transistors may be either PNP type or NPN type; the P and N referring to the positive and negative material used as the emitter, base, and collector, respectively. The PNP transistor is identified schematically by having the emitter arrow pointing to the base; for NPN transistors, the arrow points away from the base. In this lesson, we shall deal mainly with PNP transistors.

In almost all applications, operation of the transistor is controlled by the bias voltage established between the base and the emitter, this bias being classified as either "forward" or "reverse." Forward bias has a polarity which causes a comparatively large emitter current; reverse bias allows no (or only a small) emitter current. For PNP transistors, the emitter is made positive to the base for forward bias and negative to the base for reverse bias.

For our application of the transistor as a controlling switch in the power supply, we are interested in the ability of a bias of the base-emitter junction to control col-

lector current. We need to know that (1) a reverse bias applied to the emitter junction prevents collector current and, (2) a forward bias at the emitter junction allows collector current. Furthermore, this emitter junction is biased either to complete cutoff, so that there is no collector current, or it is sufficiently forward biased that the collector current is maximum (limited by the circuitry external to the transistor).[1]

Basic Power Supply Circuits

Figure 1 shows the fundamental circuitry of the transistor used as a switch. A control voltage determines the emitter junction bias; a switch is included so that the polarity of this bias voltage may be reversed. In the upper switch position, the emitter is forward biased; in the lower switch position, the emitter is reverse biased. The battery is connected between the emitter and collector. As we will see, the transistor either conducts heavily or becomes nonconductive, thus controlling the current through the transformer.

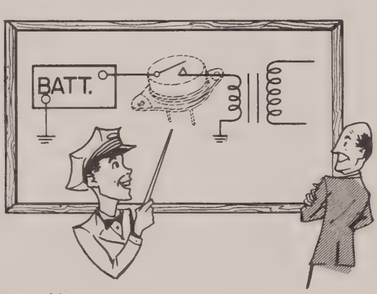
With the switch in the upper position, the control voltage A makes the emitter positive to the base and the emitter junction has forward bias. This establishes a large current between the emitter and collector. The voltage drop across the emitter-collector is now very low---a fraction of a volt---and the battery is effectively connected across the primary of the transformer. This means a high current through the transformer winding, limited only by the emitter-collector current capability of the transistor, the primary voltage and the design of the transformer.

With the switch in the lower position, the control voltage has reversed polarity and the emitter is now negative to the base; the emitter junction has reverse bias. With reverse bias, both the emitter-base current and the emitter-collector current become zero; there is no current through the transformer. It is easy to see that by reversing the switch there are alternate periods of high current and no current through the transformer. This is the same as if a square-wave voltage were applied to the primary winding. We have already said that the transistor replaces the vibrator in the power supply. If we replace the emitter-collector junction of the transistor of figure 1 with one set of contacts of a vibrator, the operation is the same. The transistor acts like a switch in which the emitter-collector circuit is alternately open and closed according to the bias of the emitter junction.

Two transistors are required for a practical switching circuit in power supply operation, and figure 1B shows the basic arrangement. The circuit for the upper transistor is the same as that of figure 1A, with the voltage across the lower half of feedback winding (F2) taking the place of the con-

1. Transistor operation is discussed in more detail in another part of the training.

trol voltage of figure 1. Transistor No. 2 has the same circuitry as the upper transistor, with the exception that the two units are connected in something of a push-pull arrangement. The collectors are connected to opposite ends of the primary winding (P1 & P2) and the bases are connected so that the control voltages of the feedback winding (F1 & F2) applied to the transistor bases cause forward bias on one transistor and reverse bias on the other transistor.



Basically, the Transistor Operates as a Switch Which Alternately Opens and Closes the Circuit from the Battery to the Transformer.

When the switch is closed, both transistors start to conduct (we will see the "starting" circuit shortly). Because these circuits cannot be in perfect balance, one transistor will initially conduct more than the other. For convenience, assume that transistor No. 1 conducts the heavier. This means that the current through the upper half of the primary winding (P1) will be greater than that through the lower half of the winding (P2), and the operation will now be controlled by the emitter-collector current of transistor No. 1.

The polarity of the voltages produced at the windings as a result of the emitter-collector current of transistor number 1 are shown. The lower half of the feedback winding (F2) has a voltage which forward biases the upper transistor. This causes a large emitter current and brings the transistor into full conduction.

While the upper transistor is conducting, the lower transistor is reverse biased, to cutoff. The voltage of the upper half of the feedback winding (F1) is a reverse bias on the emitter junction, with the result that the emitter current is zero.

The magnetizing current through the upper half of the primary (P1) increases until the core reaches saturation. (Core saturation means that any further current increase in the winding will not cause any additional increase in magnetic flux.) Without any further increase (change) in the magnetic field, there is no induced voltage in the windings. Thus, as a result of core saturation, the voltages of the feedback winding (both F1 & F2) drop to zero.

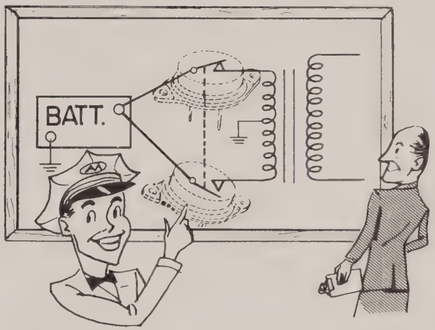
Because the voltage across F2 is now zero, both the forward bias and the emitter current of transistor No. 1 are zero. At the same time, however, transistor No. 2 is no longer reverse biased and starts to conduct. The decrease in current through the upper half of the primary winding (P1) and the increase in current through the lower half (P2) both act to induce voltages in the windings which are of

opposite polarity to those shown in the diagram. Furthermore, these induced voltages are of such a polarity that transistor No. 1 is driven to cutoff and transistor No. 2 is now in full conduction--the opposite of what happened previously. The current through primary P2 continues to rise to the point of core saturation, when, once more, the voltages of the windings reverse polarity to switch the transistors from conduction to nonconduction and vice versa.

Continuing our comparison of transistor operation with that of the vibrator, if we substitute the vibrator contacts for the emitter-collector junctions of the transistors, the circuit of figure 2 is the same as that previously shown for the vibrator. As the vibrator alternately places the battery across one-half of the primary winding and then across the other, so the transistors alternately conduct to serve the same purpose.

One of the important advantages of the transistor supply lies in the almost instantaneous reversal from one transistor to the other---the switching time is in the order of microseconds. In comparison, the vibrator contacts are open an appreciable percentage of the time. The result is lower efficiency.

The operating frequency of the transistorized power supply is determined mainly by the design of the transformer and its saturating characteristics rather than by a separate timing circuit. Thus, it is possible to operate the transistorized supply over a wide range of frequencies merely by using a suitable transformer and circuit design. Operating frequencies ranging from a few hundred to a few thousand cycles have been found to be most practical for the power supply of two-way communications equipment.



In Practical Power Supplies Two Transistors Operate as Synchronized Switches--One is Open While the Other is Closed.

The voltage waveshape at the secondary winding of the transformer in the transistorized supply is similar to that of the vibrator supply, resembling in general, a square wave. Small "spikes" at the end of each half cycle are present, but these are minimized with proper design. With suitable filtering, these spikes are removed from the output voltage waveform.

One factor important to transistor operation, which must be carefully considered in power supply applications, is the operating temperature of the transistors. Transistors operate normally and with good efficiency only when their temperature does not exceed a cer-

tain maximum. Beyond this, operation not only becomes unsatisfactory but the transistors may be damaged. By careful circuit design, the power dissipated inside the transistor can be held to a minimum. Even then, some heat is developed. By mounting the transistor on an aluminum heat sink having suitable "fins," the heat is conducted away from the transistor and the power handling capability of the transistor is improved.

Mounting the Transistors on a Heat Sink Promotes Operation Below the Maximum Allowed Temperature.

The output voltage from the transistorized supply offers no problem, for this can be controlled by the turns ratio of the transformer windings. The amount of current is limited by the current handling capability of the transistor. Where the power supply must deliver greater load currents than two transistors are capable of handling, additional transistors may be used. Transistors may be placed in parallel in the primary. Or, several primaries, connected either in series or parallel, may be used.[2]

Handie-Talkie Transistorized Supply

Figure 3 is the complete circuit of a transistorized power supply designed to operate from either a 6 or a 12-volt DC source. This supply is used in several models of the Motorola HANDIE-TALKIE, a portable two-way FM radiophone.

To meet the requirements of the transmitter and receiver, the power supply must furnish voltages of approximately 60 volts, 120 volts, 5 volts and 1.3 volts. The 5-volt source is for the transistors in the receiver and transmitter, and the 1.3 volts is for the tube filaments.

The primary power source in figure 3 may be either an internal or an external battery. The internal battery is the long-life cadmium type and produces 6 volts; the external battery may be any type and may be either 6 or 12 volts. Cable kits to the external battery provide for 6 or 12-volt operation. For 6-volt batteries, the two primaries of the transformer are connected in parallel; for 12-volt operation, these primaries are connected in series. For either connection, each primary has 6 volts applied. Switch S1 provides for an easy change of operation between internal and external batteries.

2. See TM11-690 "Basic Theory and Application of Transistors," pages 183-186.

The power transformer has two identical sets of primary and feedback windings. This allows for two complete and independent multivibrator circuits, each similar to that shown in figure 2. Each primary operates independently of the other and supplies one-half of the load current. Because the primaries and feedback windings have the same transformer core, the multivibrators operate in synchronism.

The transmit-receive relay (K1) is important to the operation of the primary circuit. This relay is energized when the transmitter is placed "on the air." With the equipment in standby, the relay is in its release position as shown, and both the 22-ohm and 1000-ohm resistors are in series with the emitter-base circuit and limit the current to the desired level. During transmission, the drain on the power supply is greater and, consequently, the transistors must conduct more heavily. The relay contacts short the 1000-ohm resistor when the relay closes and only the 22-ohm resistor is in the path between the emitter and base. This allows higher current through the transistors and satisfies the high current demand of the load.

During periods of transmission, the relay contacts also short out the 2.2-ohm resistor in series with the 1.3-volt supply line to the filaments. The transmitter requires more filament current than does the receiver, so the voltage at the transmitter filaments would be too low during transmissions if the 2.2-ohm resistor were left in the circuit.

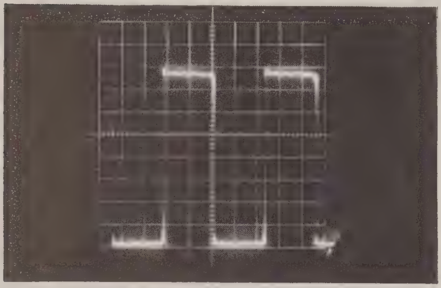
The secondary winding to the left in figure 3 serves as the source for both the 120-volt and the 60-volt outputs. The voltage of this winding is rectified in the bridge network and filtered through a pi-type filter to produce 120 volts at the output. The two lower rectifiers of the same bridge circuit rectify one-half of the voltage of the winding and provide the 60-volt output available at the center tap of the winding.

The secondary winding shown in the middle of the drawing serves to supply the 5.2-volt output for the transistors in the receiver and transmitter. The rectifiers are connected for the required negative output voltage and again a conventional pi-type filter is used. A small rectifier is connected from the output of this section to the internal battery. If the internal battery is installed when the equipment is operated from an external battery source, the rectifier provides a trickle charge for the internal battery.

Parallel rectifiers are used in the 1.3-volt filament source to handle the current requirements during transmit. Most of the stages of the transmitter use tubes rather than transistors and the filament current drain is heavy.

T-Power

The transistorized supply used for the HANDIE-TALKIE has definite power limitations and cannot be used to operate higher powered transmitters such as those found in mobile applications. Motorola has developed higher capacity transistorized supplies capable of operating 25-100 watt transmitters. The trade name "T-POWER" has been given to these supplies.



This is an Actual Photo of the Collector-Emitter Voltage Waveform of a Transistor Supply in Standby Operation.

This circuit requires a 12-volt primary source which has its negative side grounded. (Battery negative ground is true of almost all new cars, although a few trucks, etc. may have their positive battery terminal grounded.) When the switch is turned on, primary voltage is applied to (1) the emitters of the transistors through the primary winding, and (2) the bases of the transistors through the feedback winding. The full battery voltage does not reach these bases, however, for the 150-ohm feedback resistor and the 330-ohm starting resistor form a voltage divider across the supply, and the bases are connected at the mid-point of this divider. Thus, the emitter of each transistor has a higher positive potential than the base; hence, the transistors have "forward" bias. (The transistors are the PNP type.)

Forward bias on the transistors causes conduction and, again, one transistor will conduct harder than the other due to a certain amount of unbalance which is present in all circuits. This starts the multivibrator action, which is identical to that of the other circuits already discussed. Once the circuit starts to operate, the starting resistor has no further function.

It is essential to compensate for the larger current required during periods of transmission. This is the function of the low-resistance "feedback resistor" in the emitter-base circuit during transmit time. During transmission, the transmit-receive relay connects the 3-ohm resistor in the circuit; during standby, the 150-ohm resistor is connected. We have already said that the emitter-collector current depends upon the emitter-base bias and current. Thus, in order to establish a larger output current during periods of transmission, it is necessary to provide more emitter-base current. This is realized by having the smaller resistor in the circuit during transmit.

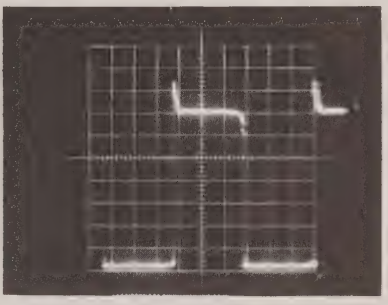
Figure 5 shows the complete circuit of the transistorized T-POWER supply. The primary circuit is identical to the simplified diagram of figure 4. The two transistors are not located on the power supply chassis, but are mounted on a heat sink on the front panel of the equipment.

Fuse F1 protects the power supply from damage due to excessive current. Also, a severe overload will normally stop the multivibrator action so that there is no excessive current due to a short in the secondaries.

The AC Power Supply

Wherever AC power is available, and where the equipment is stationary rather than mobile, it is advantageous to use the AC type of power supply. This supply is the most economical and maintainence-free. There is no need to be concerned about batteries being charged, generators working properly, etc., as is encountered in portable or mobile equipment.

The AC power supply used in FM communications equipment is no different from AC supplies used in connection with other electronic equipment. We assume, in talking about the Motorola AC supplies, that the fundamental principles of operation are known. With this in mind, we are ready to inspect figure 6, which is the circuit of a relatively low-powered supply used for several Motorola base-station receivers.



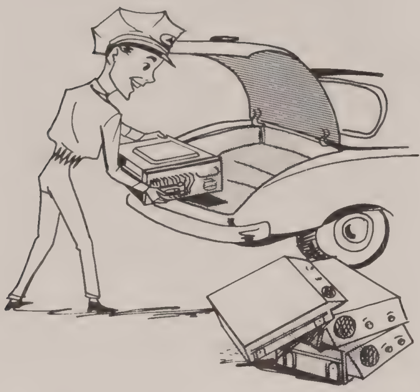
The Collector-Emitter Voltage Waveform Shows Sharper "Spikes" During Transmit--They are Due to the Higher Current During Transmit.

Receiver AC Power Supply

The 117-volt AC source is applied to the primaries of two separate transformers. The AC line is filtered by small by-pass capacitors placed from each side of the line to ground. Each primary is protected by a fuse. Transformer T2 is a filament transformer having a 6.3-volt output. Transformer T1 is a high-voltage transformer and supplies the AC required for the B plus voltage. This AC voltage is rectified in a bridge circuit consisting of 4 selenium rectifiers, chosen for their comparatively long life and freedom from replacement. The rectifier output is filtered in a conventional pi-type filter, and a high-resistance bleeder allows the capacitors to discharge when the supply is turned off. The output voltage is about 180 volts DC and is rated at 55 ma.

This, then, is perhaps the most simple form of the conventional AC power supply.[3]

3. See TM11-662, pages 144-147.



The Transistor Power Supply is Rapidly Replacing Other Types in Two-Way Mobile Radio Equipment.

AC Utility Model Power Supplies (30 Watts)

Another type of AC power supply is that which is used in the AC Utility Radio Set. AC Utility is the name applied to a model that uses a mobile-type transmitter and receiver but is powered from an AC power supply. This radio set, available with power outputs of up to 30 watts, is packaged in a mobile housing and offers a convenient, light-weight, desk-top base station.

The power supply is rather simple, using only two power transformers to furnish the same voltages and currents as does the mobile supply. The circuitry is almost the same as that of the vibrator supply with the exception of the primary. See Figure 7.

The primaries of both transformers are connected directly to the 117-volt AC supply line through protective fuses. Transformer T1 has two low-voltage secondaries. The lower winding supplies 6.3 volts for the filaments of the receiver and transmitter tubes. The upper winding is used as the control voltage source to energize the relays, etc. For this purpose, a conventional full-wave rectifier section is included to supply a DC output.

Transformer T2 has three secondary windings which correspond to the same windings used on the vibrator transformer. The lowest secondary winding is used for the bias source for the transmitter power stages. This secondary voltage is rectified and filtered as required. The other two secondary windings are used for the high-voltage supplies for the receiver and transmitter. The middle winding is the supply for the receiver; the upper winding is for the transmitter. However, during transmission, the voltage normally fed to the receiver is used for the transmitter.

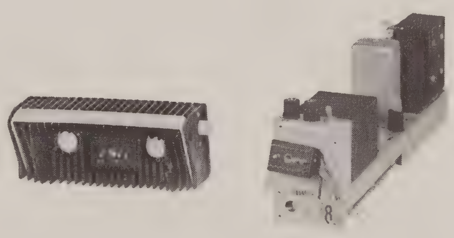
During periods of transmission, transmit-receive relay K1 is energized. As shown in figure 7, one side of the relay coil is connected to a low, positive DC voltage source. The other side of the relay coil is grounded when the operator depresses the microphone press-to-talk button. With relay K1 energized, several things happen:

1. Contacts 5 and 6, and 12 and 13 of relay K1 "make" and apply AC voltage from the secondary of T2 to rectifiers CR2 and CR3. The resulting rectified (DC) voltage is added to that voltage developed by the receiver section of the power supply (C2 and C3 connected to ground through C4 and C5) so that the combined DC available amounts to 425 volts.
2. Contacts 7 and 8 of relay K1 "make" to feed the 425 volts DC to the transmitter.
3. Contacts 9 and 10 of relay K1 "break" to remove DC voltage from the receiver, while contacts 10 and 4 "make" to feed this same DC voltage to the transmitter for powering the oscillator section. Additionally, resistors R9 and R10 form a voltage divider from this DC source to lower the voltage for use in the microphone circuit.
4. Contacts 3 and 4 of relay K1 "make" to energize the antenna switchover relay mounted on the transmitter chassis. This relay switches the antenna from the input of the receiver to the output of the transmitter.

Another voltage available during transmission is that feeding the multipliers and power amplifier screen circuits of the transmitter. This voltage is taken from the center tap of the upper secondary winding of transformer T2. Two separate DC voltages connected in series make up this voltage. Section A of rectifiers CR2 and CR3 serve as full-wave rectifiers for the secondary voltage, the active voltage at each rectifier being that of one-half of the winding. This voltage is also in series with the receiver B voltage, due to the connection of the rectifiers to the positive side of the receiver supply, so the final value will be the sum of these separate voltages. Dropping resistors R6, R7 and R13 reduce the voltage to the desired value and the type 47 pilot lamp serves as a fuse and prevents rectifier damage due to overloads. Resistor R12 and switch S1 allow for full or reduced voltage to be applied to the power amplifier screen ground. The low voltage is required during alignment procedures.

30–60 Watt AC Supply

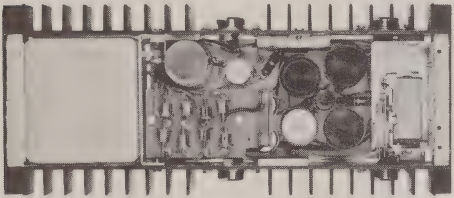
Figure 8 shows the circuit of a typical power supply capable of operating a 30-60 watt transmitter and a receiver. The schematic for either the 30 or the 60-watt



The Transistors of this Mobile Power Supply are Mounted on an External "Heat Sink."

power supply remains the same; the difference is in the ratings of the component parts and the voltages supplied by the transformer.

Primary power of 117 volts is applied directly to the primaries of transformers T2, T3 and T4. The circuit of transformer T1 remains inactive until the transmitter is placed "on the air." (AC is then applied to its primary through relay contacts 8 and 9.) Each of the primaries is protected from overloads by its own fuse.



This Power Supply Utilizes Two Heat Sinks, One on Each Side, to Provide Maximum Cooling for the Transistors.

Transformer T2 supplies filament voltage for the transmitter tubes and for the filaments of the high-voltage rectifier tubes, V1 and V2 in the diagram. Transformer T3 has two low-voltage windings. The 6.3-volt winding is the filament supply for the receiver and the other winding is utilized as relay central voltage, etc. This voltage is first rectified and filtered to provide 6 volts DC.

Transformer T4 furnishes the high-voltage for the receiver. The secondary voltage is rectified by a full-wave bridge circuit and filtered in a conventional pi-type filter section. Resistor R5 at the output serves to discharge the capacitors of both the receiver and filter when the primary power is removed. Resistor R12, in series with the supply lead to the receiver, serves the same purpose as a fuse: it protects the rectifiers from overloads, particularly shorts in the wiring leading to the receiver circuits.

With transformers T2, T3 and T4 in operation at all times, the filaments of both the transmitter and receiver are in constant operation, the filaments of the high-voltage rectifiers of the transmitter supply are heated and ready for instant operation, the positive 6-volt supply is present, and the receiver B plus places the receiver in operation.

In order to transmit, the transmit-receive relay must be energized. One side of the relay coil connects directly to positive 6 volts. To energize the relay, the other relay terminal must be grounded. This terminal side of the relay coil connects to terminal 16 of the terminal board shown at the bottom of the figure. This circuit leads to a series connection between the interlock switch, the press-to-talk switch on the operator's microphone, and ground. The interlock switch is closed only when the door of the base station is shut. With the door open, the circuit to the operator's press-to-talk switch is open---the high voltage power supply will not operate. This protects the service-

man who may be working on the transmitter or power supply; as soon as he opens the door, the high-voltage supply cannot be turned on.

With the interlock switch closed and the operator's press-to-talk button depressed, relay K1 energizes. Several things then happen simultaneously.

1. Contacts 8 and 9 of relay K1 "make" to apply AC power to transformer T1. The high DC output voltage (400 volts) is fed to the transmitter. Resistor R3 drops the high voltage to a lower value (275 volts) for powering the low-voltage circuits in the transmitter.

2. Contacts 4 and 5 of relay K1 "break" to open the voltage supply line to the receiver---the receiver is thus "muted." Filament power, however, remains connected to the receiver.

3. Contacts 2 and 3 of relay K1 "make" to provide a negative bias voltage for the transmitter. This voltage is derived from the negative return path of the high-voltage supply and resistor R2.

4. Contacts 11 and 12 of relay K1 "make" to provide positive 6 volts for operation of the antenna relay mounted on the transmitter chassis. This relay switches the antenna from the input of the receiver to the output of the transmitter.

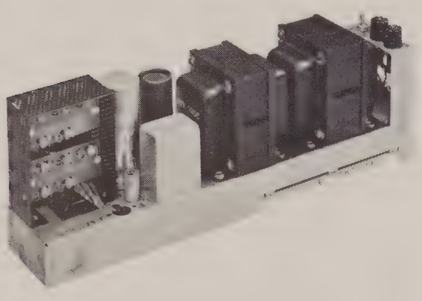
5. Through the action of transmit-receive relay K1, 117 volts AC and 6.3 volts AC is made available for operation of auxiliary circuits. Switched 117 volts may be used to operate a cooling blower during transmission. Switched 6.3 volts is used to light a red indicator on the control panel---this tells the operator the transmitter is "on."

250-Watt Power Supply

The power supplies so far mentioned are suitable for operating receivers and low-power transmitters. We shall now discuss a power supply capable of operating a 250-watt final amplifier. In addition to supplying the necessary power, this type of supply must necessarily include more elaborate protective and control devices.

Figure 9 is the schematic of a typical power supply designed for the Motorola 250-watt transmitter. Input power is connected to fuse block E2. Either three-wire 230-volt, single-phase or two-wire 117 volts single phase primary power may be used. In order to turn "on" the high-voltage supply, high-voltage switch S1 and AC power switch S4 must be closed. The common lead of the primary source (terminal board #12) is always connected to one side of the filament transformer T3, filament transformer T2, and 30-second de-

lay timer and plate contactor relay K3. Hence, with S1 closed, 117 volts is applied to T3, T2 and timer I1. This allows a warm-up period for the filaments of the high-voltage rectifiers and the final amplifier tubes before the high voltage can be applied. Delay is provided by timer I1. The timer motor starts with application of AC power and, after 30 seconds (this timing is variable), its contacts close. The contacts remain closed until the 117-volt source is removed from the timer motor.



This is an AC Power Supply Intended for Base Station Operation. The Secondary Circuit Includes Silicon Rectifiers, Seen at the Very Left.

Once the contacts have closed, the high-voltage supply is ready for normal operation. When the operator is ready to transmit, he depresses his microphone press-to-talk button. This applies 6 volts DC to the coil of control relay K1, energizing this relay and causing its contacts to close. 117 volts is now applied through the timer contacts, control relay contacts and through the overload relay contacts, to the plate contactor relay, K3. Thus, in order for the plate contactor relay to work, several conditions must exist; the timer must be in operation for at least 30 seconds, the control relay must be operated, and the overload relay must be in its normal release position. Furthermore, in order for the operator to close the control relay, the interlock switches on both the back and the front of the equipment cabinet must be closed. These switches are in series with the 6-volt control line and, if either door is open, the operator cannot turn the equipment on from the remote control unit.

As soon as plate contactor relay, K3, is energized, AC power is available to the high-voltage transformer and to a blower used for cooling the final amplifier tubes. If high-voltage switch S3 (at T1 transformer primary) is closed, high-voltage AC is applied to the rectifier plates. The resulting high-voltage DC output is filtered by L1 and C1 and is available for the plates of the final amplifier tubes. This same supply line is used for the final amplifier screen grids, with resistors R1 and R2 providing the necessary voltage drop. To provide the desired screen voltage, resistor R2 is variable. Resistors R3, R4 and R5 are multiplier resistors for the high-voltage meter, with R5 being adjustable in order to calibrate the meter. For this purpose, the high voltage is measured with an accurate meter and compared with the reading on the meter on the cabinet. If incorrect, R5 is adjusted accordingly.

Overload relay K2 offers protection to all high-voltage circuits should current demands become excessive. As shown on the schematic and the simplified sketch of figure 10, this relay has a double coil. One coil, shunted by overload control R3, is wired directly in series between ground and the center tap of higher voltage transformer T1. Hence, full current of the high voltage circuit flows through this parallel arrangement of control R3 and the relay coil. When R3 is properly adjusted, relay K2 will operate when the current exceeds 325 milliamperes.

With such an occurrence, the following takes place: 117 volts will be removed from the coil of plate contactor relay K3 and this relay will de-energize. Contacts of this relay then disconnect AC from the primary of high-voltage transformer T1. Thus, high DC voltage is immediately cut off. The other contacts of overload relay K2 and the second coil of this relay provide a "locking" circuit for relay K2. That is, as soon as K2 energizes, it locks itself in the energized position until the operator releases the microphone press-to-talk button. (Lock-in is used to eliminate undesirable relay clatter.) As soon as the operator releases the button, the circuit resets itself and is ready once again for normal operation. However, when the operator depresses the button again, if the overload condition still persists the overload protection circuit will operate once again.

Before the final amplifier stage of the transmitter is fully adjusted, it is desirable to have reduced power applied. Until the plate tank is tuned, it is possible that the plate current would become excessive and actuate the overload relay. To offset this, HI-LO switch (S2) allows for reduced plate and screen voltage. A resistor, controlled by the HI-LO switch, is placed in series with the primary of the high-voltage transformer, and the reduced voltage is about one-half its normal value. The final is first adjusted to near its final correct setting; the switch can then be flipped to HI without causing excessive plate and screen currents.

In order to compensate for variations of line voltage, both filament transformers T2 and T3, have adjustable taps so that the secondary voltage to the filaments will be correct. Variations in the plate transformer voltages are not so critical. Bias resistor R6 in the secondary circuit of transformer T3, provides an adjustable source of protective bias for the tubes of the transmitter final amplifier.

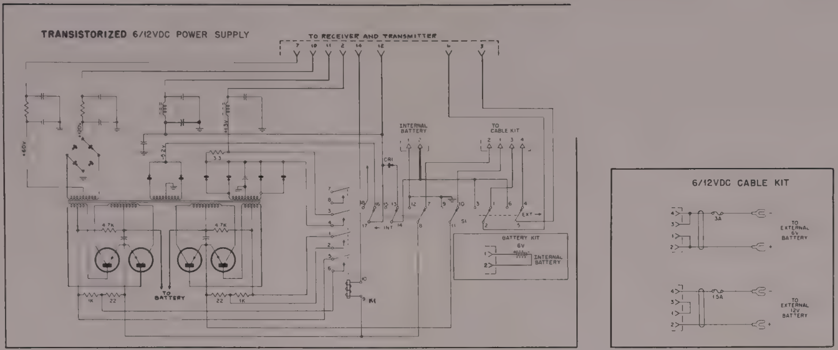


FIGURE 3

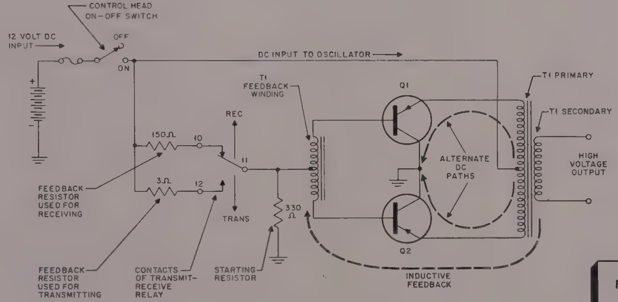


Figure 4.

FIGURES 1 and 2 are on the back of this page

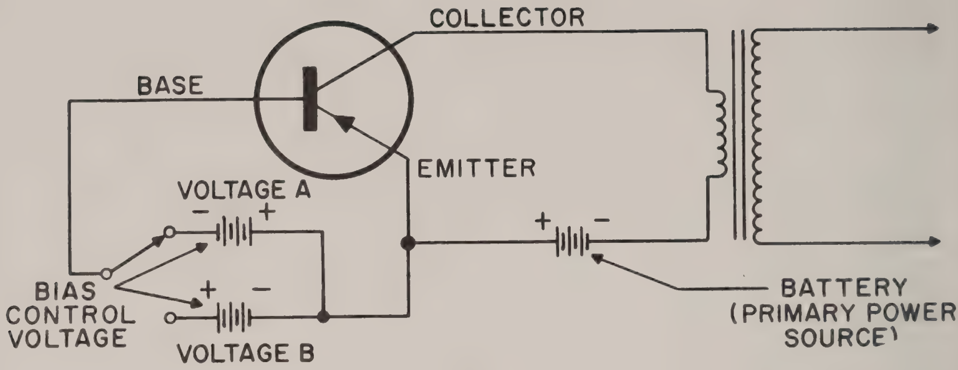


FIGURE 1

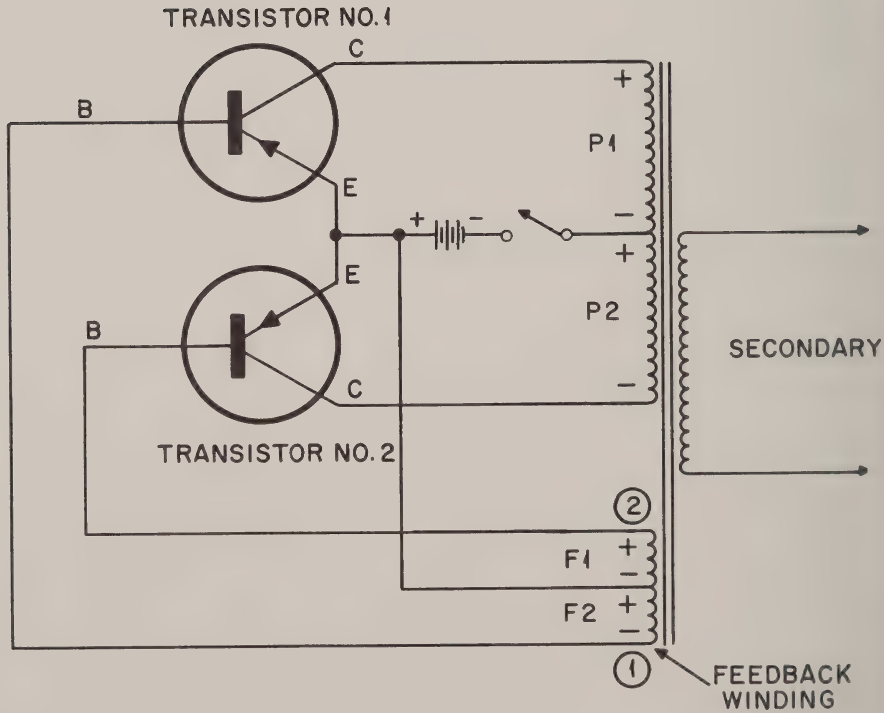
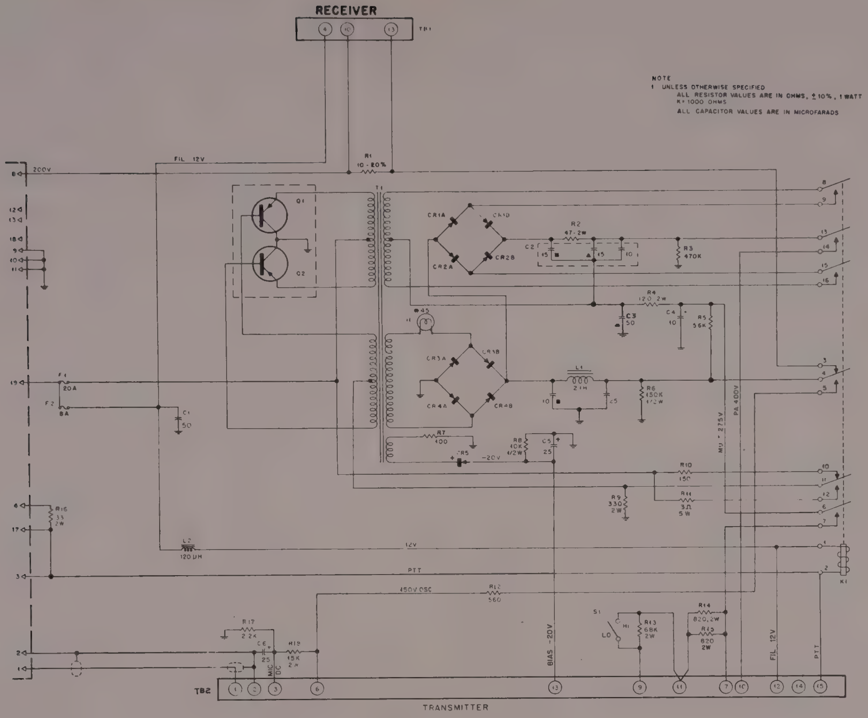


FIGURE 2

STUDENT NOTES

STUDENT NOTES

STUDENT NOTES



POWER SUPPLY MODEL TU549
FIGURE 5

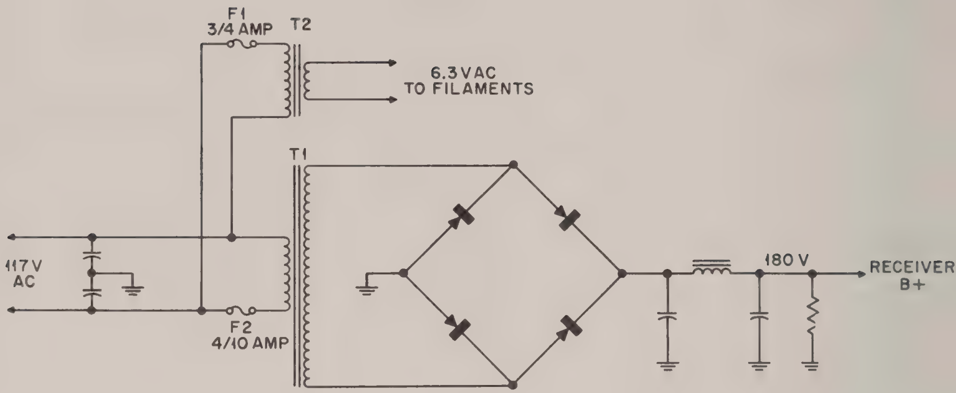
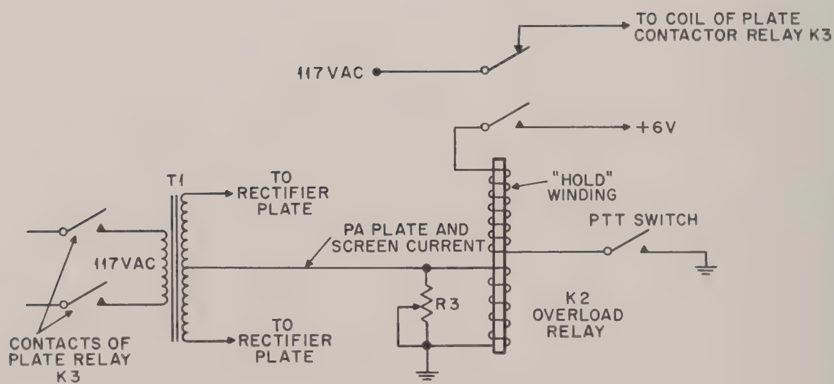


FIGURE 6

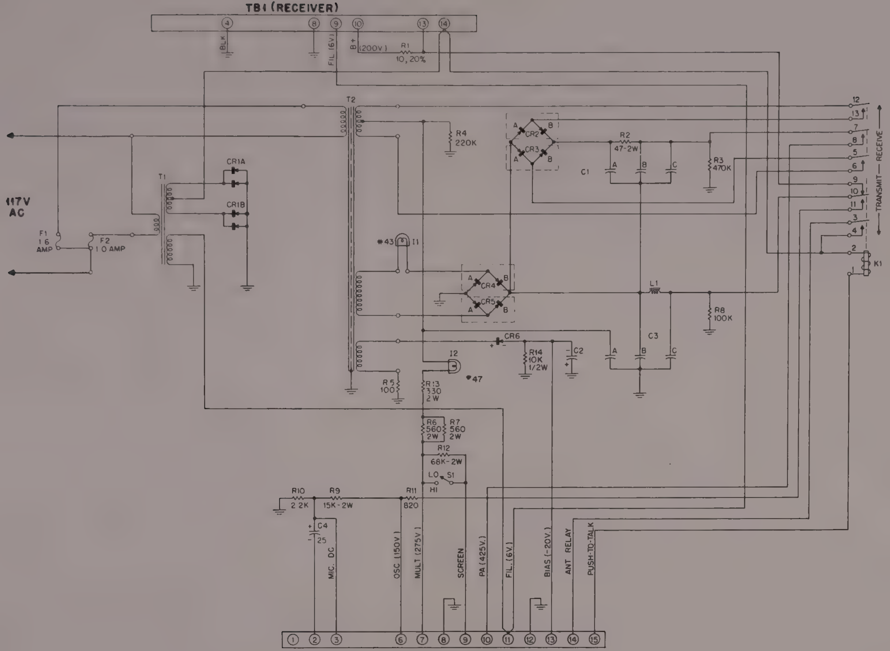


BASIC OVERLOAD CIRCUIT
FIGURE 10

STUDENT NOTES

STUDENT NOTES

STUDENT NOTES

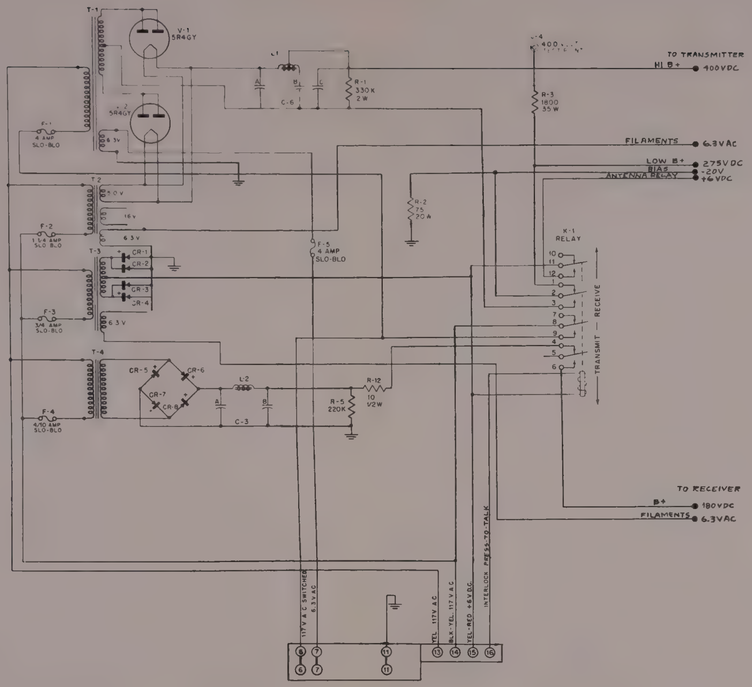


AC POWER SUPPLY
SCHEMATIC DIAGRAM
FIGURE 7

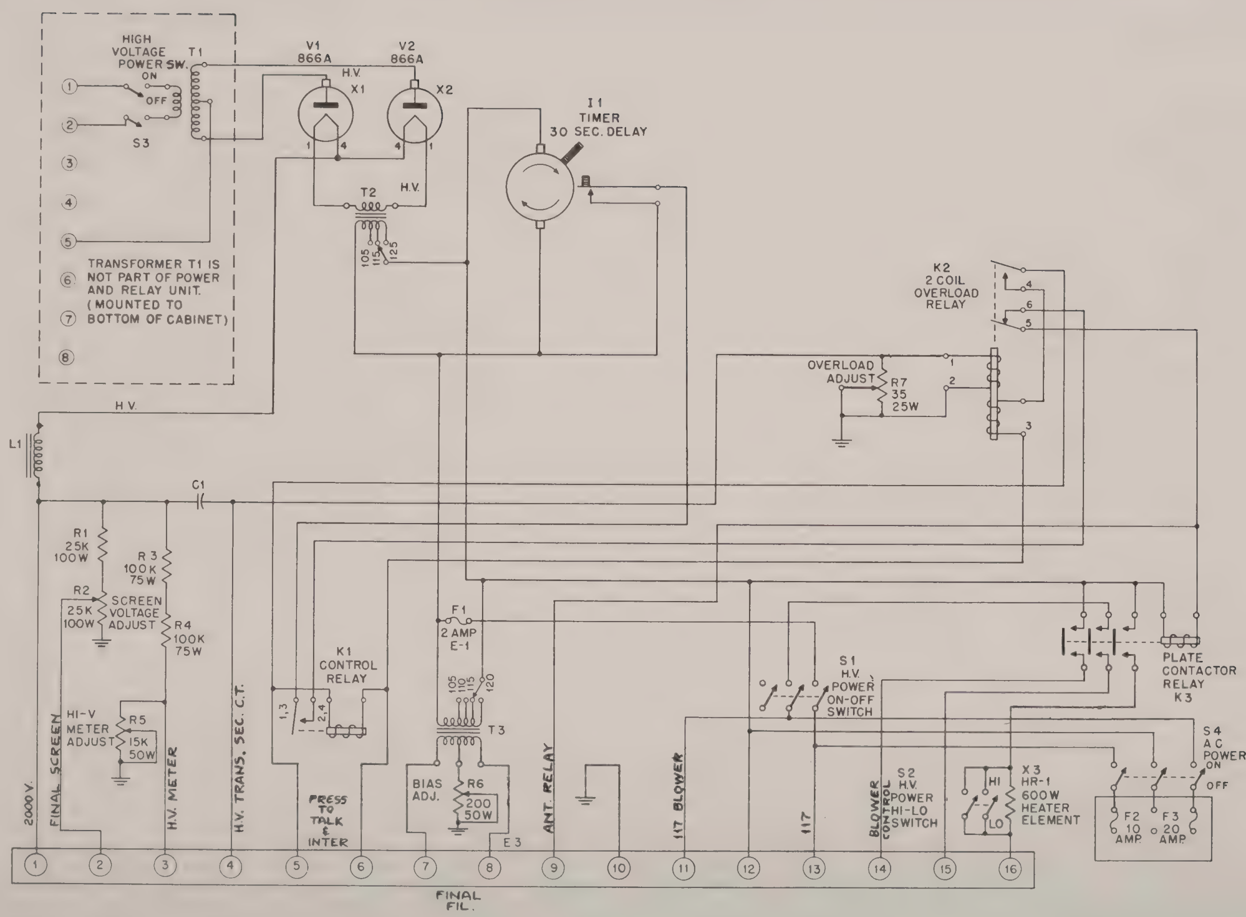
STUDENT NOTES

STUDENT NOTES

STUDENT NOTES



AC POWER SUPPLY
FIGURE 8



HIGH VOLTAGE POWER SW.
ON
OFF
S3
T1
TRANSFORMER T1 IS NOT PART OF POWER AND RELAY UNIT. (MOUNTED TO BOTTOM OF CABINET)
V1 866A
V2 866A
H.V.
X1
X2
T2
I1 TIMER 30 SEC. DELAY
K2 2 COIL OVERLOAD RELAY
OVERLOAD ADJUST
R7 35 25W
L1
C1
R1 25K 100W
R2 25K 100W
SCREEN VOLTAGE ADJUST
R3 100K 75W
R4 100K 75W
HI-V METER ADJUST
R5 15K 50W
K1 CONTROL RELAY
F1 2 AMP E-1
T3
BIAS ADJ.
R6 200 50W
S1 H.V. POWER ON-OFF SWITCH
PLATE CONTACTOR RELAY K3
S4 A C POWER ON OFF
S2 H.V. POWER HI-LO SWITCH
X3 HR-1 600W HEATER ELEMENT
HI
LO
F2 10 AMP.
F3 20 AMP.
2000 V.
FINAL SCREEN
H.V. METER
H.V. TRANS. SEC. C.T.
PRESS TO TALK & INTER
E 3
ANT. RELAY
117 BLOWER
117
BLOWER CONTROL
FINAL FIL.

FIGURE 9

national

MOTOROLA

RADIO COMMUNICATIONS

service

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-12
ANTENNAS

Antennas and Transmission Lines

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON TA-12
ANTENNAS

Antennas and Transmission Lines

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

ANTENNAS AND TRANSMISSION LINES

Lesson TA-12

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Emergency service organizations have been using radio for many years. Today, a two-way radio antenna rising from a well-run automobile service station is commonplace.

ANTENNAS AND TRANSMISSION LINES

Lesson TA-12

Introduction

The success of any communications system depends upon the proper operation of its antennas and transmission lines no less than upon its transmitters and receivers. This is something that the service technician must remember when he is working with two-way communications systems. Unless the radiated signal reaches the receiver with sufficient power, satisfactory communications cannot be established.

The antenna, transmitter, and receiver are not the only factors involved, however. Sometimes the antenna of a mobile vehicle will be in a dead zone, an area where there just isn't any signal present. This is very possible in the vicinity of tall buildings, hills and other obstacles. Or the vehicle may enter a very noisy area, where the received signal must compete with a high noise level. Still another factor is the possible desensitization of the receiver by strong signals from a nearby transmitting antenna.

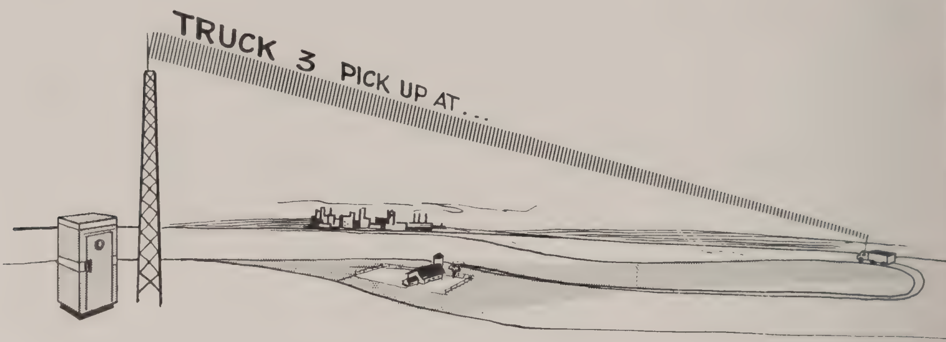
Thus, although the receiver, transmitter and power supply may be the first place to look for trouble, the serviceman must be keenly aware that the antenna system and the conditions of propagation are also potential sources of trouble and they must not be overlooked. He must be particularly aware of the characteristics of radio waves and be able to recognize any effects they may have on the operation of a communications system.

Throughout this lesson we shall deal with three main subjects: (1) the radiating electromagnetic wave, (2) the operation and characteristics of antennas and transmission lines, and (3) the types of antennas used in two-way communications systems. We shall begin with the radio wave.

Types of Radio Waves

The RF power available at the final amplifier stage of the transmitter is fed to the antenna by means of a transmission line. The RF voltage and current in the antenna produce electric and magnetic fields, respectively. These fields radiate from the antenna, becoming electromagnetic (radio) waves. They travel through space at a rate of 300,000,000 meters (approximately 186,000 miles) per second.

The radio wave may reach the receiving antenna by any of three paths: (1) It may travel in a nearly straight line between the two antennas. This requires the antennas to be in a "line-of-sight,"



For Reliable and Consistent Operation, Two-Way Radio Systems Make Use of Direct Waves Between the Base Antenna and the Vehicle.

free from intervening obstructions. (2) It may be reflected from some obstacle such as a tall building, much the same as a light beam is reflected from a mirror. (3) It may encounter the ionosphere and be "bent" back toward the earth. At very high frequencies there is little or no bending of the waves from the ionized layers and two-way communications must depend on either the direct path or the reflected path.

Thus only the first two paths are relied on for radio communications. Signals in the lower bands are periodically returned to earth from the ionosphere, but usually at a great distance from the transmitter. These "sky waves" are also sporadic and unpredictable, hence unreliable for sustained communications. Direct or reflected waves, on the other hand, are dependable; they do not change appreciably from hour to hour or from day to day in their propagating characteristics.

The radio wave is radiated through space in much the same manner as a light wave. Light waves have very high frequencies and they do not bend as much as lower frequency waves in their travel through space. The higher the frequency of a radio wave, the more it tends to resemble light in its propagation characteristics. There is always some bending of radio waves even at high frequencies, however, so for practical calculations the range is somewhat greater than the line-of-sight distance. The exact amount of additional coverage depends upon the frequency, carrier power, atmosphere conditions and numerous other factors.[1]

Wave Motion

We have said that the RF current and voltage in the antenna set up magnetic and electric fields about the antenna, and that these fields make up the radio wave. It might be well at this point to study the nature of these fields more closely.

1. See TM11-666, pages 10-43.

The current in the antenna is first maximum in one direction, then decreases to zero and starts to increase in the opposite direction. Each time the current is zero, large voltages exist between the ends of the antenna. Thus we have electric fields caused by the voltage as well as the magnetic fields caused by the current.

The two fields are shown in figure 1. The magnetic field (1A) is represented by concentric circles about the antenna, the antenna length passing through their center. This field moves away from the antenna and becomes the magnetic component of the radio wave.

One-quarter cycle after the current reaches maximum it decreases to zero, and the voltage between the ends of the antenna becomes maximum. Figure 1B shows the resulting electric field about the antenna. This field also moves away from the antenna, but it is referred to as the electric component of the radio wave.

We now have two fields radiating from the antenna. The direction of the magnetic field is perpendicular to the length of the antenna while the direction of the electric field is parallel with the antenna length. The two fields are thus at right angles to each other as they radiate from the antenna.

The arrow in figure 1A indicates the direction of the current through the antenna. When the arrow points up, the current produces magnetic lines about the antenna--and the lines are clockwise. When the current reverses its direction (during the next half-cycle), the magnetic lines also reverse (becoming counterclockwise). The electric field behaves in the same way, expanding first in one direction and then in the other. The high operating frequencies used in two-way communications equipment cause the fields about the antenna to go through millions of complete changes like this each second.

The radio wave is analogous to the waves caused by dropping a stone in a pool of water. The stone produces water waves and causes them to radiate horizontally from the center, but the water itself only rises and falls--only the disturbance moves outward. The antenna can be thought of as radiating electromagnetic disturbances in all directions from the antenna, although in this case the medium through which the waves pass is quite different. If only one stone is dropped in the pond the waves soon die out, but if a number of stones are dropped in succession so that the waves follow each other in an orderly fashion, the situation becomes quite similar to that caused by the antenna. The radio waves are produced by an orderly succession of phenomena which create the fields already described, and these fields are continually being built up about the antenna and radiated through space. Radio waves are thus made up of an orderly succession of events rather than a series of discontinuous pulses.[2]

2. See TM11-666, pages 1-7.

Wave Polarization

The direction of the electric and magnetic fields with respect to the earth depends upon the position of the radiating antenna. As a means of identifying the position of these fields, we use the term "polarization" to indicate the direction of the electric field with respect to the earth. As far as the antenna is concerned, the electric field exists between the two ends (considering straight wire antennas only), so the direction of the electric field corresponds to the direction of the antenna wire. A vertical antenna will thus produce a vertically polarized wave. For optimum reception of any signals, the position of the receiving antenna must be the same as the polarization of the received signal.[3]

Wavelength

With the speed of propagation remaining at a constant 300,000,000 meters per second, the spacing between successive waves will depend upon the number of waves produced per second. If the transmitter frequency is 300 mc, for example, there must be 300,000,000 cycles of energy extending over a distance of 300,000,000 meters. This allows 1 meter for each wave, so the wavelength is then one meter. For signals of higher frequency, the wavelength must be shorter as more waves are crowded into the same space. For lower frequencies, the wavelength is longer.

Wavelength can also be analyzed by considering the time it takes to complete each cycle of current and voltage in the antenna. If a high-frequency signal changes through its complete cycle in a short period of time, the wave front will not travel far through space before the next cycle begins. The wavelength is then short. If the frequency is low, however, each cycle will require a longer period of time and each successive wave can travel farther into space before the next cycle begins.

The wavelength corresponding to a specific frequency may be found by dividing the constant 300,000,000 by the frequency. A more practical formula consists in dividing the frequency (in megacycles) into 300. Example: Find the wavelength of a 30-mc signal. Dividing 300 by 30, we get a wavelength of 10 meters. When "hams" (radio amateurs) speak of "working the 10-meter band," they are referring to a group of frequencies close to 30 mc.

Let's inspect the wavelengths of those frequencies which have been assigned to two-way communications services. The low band, according to our formula, is roughly from 6 to 10 meters. The high band becomes approximately 2 meters. Both the 450-mc and 900-mc bands have wavelengths of less than 1 meter.[4]

3. See TM11-666, page 8.

4. See TM11-666, pages 2-4.

The intensity of a radiated wave is usually determined by measuring the strength of the electric field. This intensity is usually expressed in volts (or microvolts) per meter, which is an indication of the voltage produced in a conductor one meter long when positioned in the same direction as the incoming electric field and at right angles to the direction of propagation.

These free-space considerations, however, do not take into account many "losses" introduced by the propagation path of the two-way transmission, with the result that the signal reaching the receiver may be well below the anticipated value.

The power of the wave (assuming free-space conditions) also

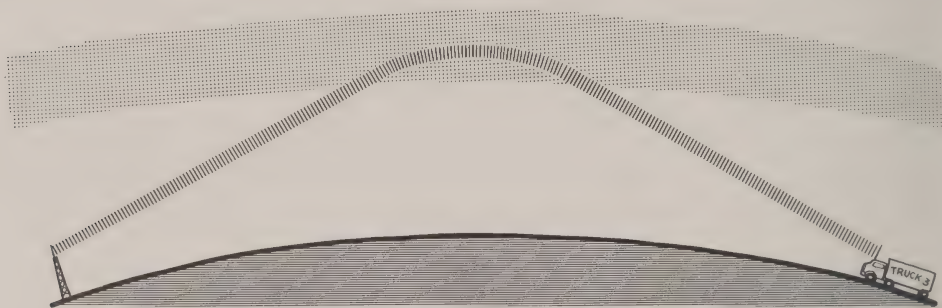
The Same Antennas and the Same Direct Waves are Used When the Vehicle "Talks Back" to the Base Station.

When we consider free-space conditions, the field intensity of a radiating electromagnetic wave decreases in proportion to its distance from the radiating antenna. For example, if the field intensity of a particular wave is 30 microvolts at a distance of 10 miles from the antenna, then at twice the distance (20 miles) we can expect to measure an intensity of 15 microvolts. The field intensity, as determined by the electric field, thus varies inversely with the distance of the field from the radiating antenna. (This of course is assuming that the propagation path is constant and that there is no obstruction of the radiating wave.)

decreases in proportion to distance, but it varies inversely with the square of the distance. Let's use another example to show this relationship. We shall assume that the field intensity at 10 miles from the transmitter antenna is 1 volt per meter. At 20 miles the intensity will then be one-half volt. To determine the power we apply the formula $W = E^2 \div R$. If we let R equal 1 ohm, the "R" can be omitted from our calculations. According to the formula, when the field strength is one volt the power will be one watt. At twice the distance, the field strength will be one-half volt and the power one-fourth watt. (These values

were chosen for convenience only; under normal conditions such large values are not likely to be encountered, nor will the free-space relationships occur.)[5]

in all horizontal directions, with no radiation directly above the antenna. The three-dimensional sketch to the right of the figure better illustrates this coverage.



Low-Frequency Waves are Often Refracted by Ionized Layers to Earth Beyond the Horizon Distance. These Waves Do Not Provide Reliable Two-Way Radio Communications.

Radiation Pattern

The radiation pattern tells us the direction in which energy is radiating away from the antenna. The selection of a particular type of antenna for a given application is determined to a large extent by the nature of its radiation pattern.

When we likened the propagation of a radio wave to a stone being dropped into a pond of water, we saw that the disturbance spread out from the center in all directions, horizontally. This is essentially the radiation pattern from a straight single-wire antenna, positioned vertically, and the pattern can be compared to a doughnut. Figure 2 shows the radiation pattern of a grounded quarter-wave vertical antenna, the type most often used in mobile applications. The top and side views of the pattern indicate a coverage

The radiation pattern of figure 2 is called "omnidirectional." Radiation is in all horizontal directions. This is generally the desired pattern for mobile two-way communications, but in certain installations the omnidirectional characteristic is not required--it may even become objectionable--and antennas having more favorable patterns must be used. Directional antennas are discussed in detail later in this lesson.[6]

Ground Waves and Sky Waves

The radio wave, you will recall, may reach the receiving antenna by one or more of several paths. Radio waves having a frequency below 30 mc are usually bent back toward the earth when they encounter the ionosphere. Two-way radio communications, however, usually make use of frequencies

5. See TM11-666, pages 8-10.

6. See TM11-666, pages 89-97.

above 30 mc, not relying on the bending of the waves by the ionosphere. This does not mean that ionospheric reflection does not take place--it occurs periodically, particularly in the low band (24-54 mc). For continued and reliable operation, however, it is necessary to depend upon the ground or "direct" wave.

This wave is characterized by its relatively straight path between the transmitting antenna and the receiving antenna, but there is still some bending due to the troposphere, the amount depending upon conditions such as temperature and humidity. The actual distance is thus sometimes appreciably greater than the distance limited by the earth's curvature (called the horizon distance). As a general rule, the actual distance of a transmission is about one-third greater than the horizon distance.

All ground waves are not "direct" waves; some are reflected. Besides the direct-path propagation, it is a property of radio waves that they may be reflected from various surfaces as light waves are reflected from a mirror. These waves may be reflected from hills, buildings, the ground itself, or from other objects. In metropolitan areas, buildings often prevent the establishment of direct paths between antennas. Operation then depends on the bouncing of these waves between buildings. At the higher frequencies this effect is so great that the buildings act like wave guides, actually providing more continuous coverage than the lower frequencies.

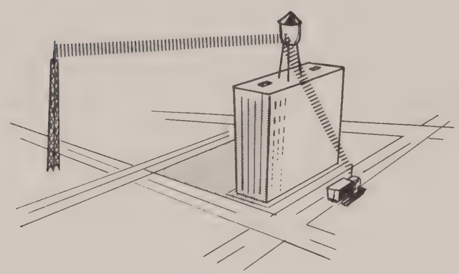
Summary

Our discussion of the radio wave and its propagation can be concluded at this point with the following summary:

1. Radio waves are electromagnetic radiations which are composed of a magnetic field and an electric field. These fields are at right angles to each other and at right angles to the direction of travel. They exist alternately with respect to time, the energy being interchanged between the magnetic field and the electric field. Unless these alternations continue, the wave cannot propagate through space.

2. Radio waves travel at the speed of light, 300,000,000 meters per second. Because of this constant rate of propagation, the wavelength of a radio wave is a function of the frequency. The wavelength (in meters) equals 300 divided by the frequency (in megacylces). Radio waves spread out in all directions from the antenna. The pattern of radiation from a straight wire antenna resembles a doughnut with the antenna centered in the hole.

3. Polarization as applied to the radio wave refers to the direction of the electric field with respect to the earth. A vertical wire, for example, produces a vertically polarized wave. For best reception, the receiving antenna must have the same polarization as the incoming wave.



High-Frequency Waves are Reflected from Objects and Often Provide Communications Which Otherwise Would be Impossible. This Effect is Particularly Helpful to 450 MC Two-Way Systems.

4. The field intensity of a radio wave is the measure of the electric field. The field intensity is usually measured in "microvolts per meter." This varies inversely with distance in free space. The power of the radiated wave, however, varies inversely with the square of the distance.

5. Radio waves may reach the receiving antenna either as sky waves or as ground waves. At the frequencies assigned to two-way communications the sky wave is not reliable, and the ground wave is used instead. Due to reflection and to some bending of the waves, reception is usually possible at some distance beyond the horizon.

Basic Antenna Action

The antenna has properties of capacitance, inductance, and resistance which enable it to become a tuned circuit at the operating frequency of the system. It must therefore be considered as an integral part of the communications system, along with the transmitter and receiver.

A tuned circuit allows maximum current (through the coil) and produces maximum voltage (across the capacitor). In a basic half-wave antenna, the ends are points of high voltage and the center is a point of maximum current. These currents and voltages produce strong magnetic and electric fields about the antenna, and these fields radiate from the antenna.

If the antenna is resonant to the frequency of the applied RF and if the antenna impedance matches the impedance of the source, the antenna will have its greatest efficiency and it will radiate maximum power.[7]

Basic Types of Antennas

Antennas are usually of the resonant type, being either half-wave or quarter-wave. The basic type is the half-wave or Hertz antenna. At the end of the antenna there is no further path for current, so the current at this point is always low--theoretically it is zero. This is a point of high voltage, however. One-quarter wavelength from the end (the center of the half-wave antenna), the condition is reversed--the current is maximum and the voltage is minimum. Conditions are always the same at both ends of the antenna, high voltage and low (or zero) current.

7. See TM11-666, pages 54-66.

While the Hertz or half-wave antenna can be regarded as the basic resonant antenna, the one most often used in two-way communications, especially in mobile systems, is the quarter-wave (or Marconi) antenna. The two antennas are similar in their action, for the "ground" supplied with the quarter-wave antenna looks like the second half of a half-wave antenna as far as the antenna current and transmission line are concerned. The impedance of the antenna is different, however, and the antenna is not as efficient in radiating RF power.

Currents flow in and out of the ground the same as in the half-wave antenna, and the end of the antenna remains a point of low current and high voltage. The grounded end of the antenna, however, is a point of low voltage and high current.

Antenna Impedance

Antenna impedance (Z) is the ratio of the voltage (E) to the current (I) at the point where the impedance is to be determined. This means that the impedance of a half-wave antenna is relatively high at the ends, where the voltage is high and the current low, and that the impedance is relatively low at the points where the voltage is low and the current is high.

If the current at the end of the antenna were actually zero, the impedance at this point would be infinite (where $Z = E \div I$), but the current is not actually zero. There are some RF losses at the end of the end of the antenna, due mostly to capacitive effects, and this reduces the end impedance. For practical purposes the end impedance is generally considered to be about 2,500 ohms. At the center of the half-wave antenna (where the current is high and the voltage low), the theoretical impedance is calculated to be 73 ohms for an infinitely thin wire. In practical antennas, however, this impedance may be considerably lower than 73 ohms.[8]

On the basis of the above calculations, we see that the impedance of a half-wave antenna can be anything from a low to a high value. If the transmission line connects to a point of high voltage, the impedance is high and the antenna is said to be voltage fed. If the transmission line connects to a point of high current, the impedance is low and the antenna is said to be current fed.

Transmission Lines

The transmission line is a device for transferring RF energy from one point to another. Specifically, it is used to transfer the RF output of the transmitter to the antenna. It is possible to connect the antenna directly to the transmitter, but the antenna is generally located some distance away. In vehicular installations, for example, the antenna is mounted outside and the transmitter inside. Even this short distance requires

8. See TM11-666, pages 66-67.

a transmission line in order to convey the RF from the transmitter to the antenna. Coaxial types of transmission lines are used almost exclusively in two-way communications.

The characteristic impedance of the transmission line is determined by its physical structure. For coaxial types, the diameter of the inner conductor and the spacing between the inner conductor and the shield determine the impedance to a great extent. Other important factors are the material used for the conducting surfaces and the nature of the dielectric material.

A transmission line may be known as "long" or "short" regardless of its absolute physical length, these terms being used in a relative sense only. A line is described as being long or short according to whether it is longer or shorter than the RF wave being transmitted on it. If the RF wavelength is less than the physical length of the line, the latter is called a long line. If the RF wavelength is greater than the physical length, it is called a short line.[9]

Transmission Line Losses

Transmission line losses are largely determined by the type of dielectric, but these losses also increase with frequency, due to the smaller capacitive reactance between the conductors.

Specially constructed lines designed to handle high RF power are available for high-frequency transmission. The charts of figure 3 indicate the efficiency of the common types of transmission lines used in two-way communications at frequencies within all 3 frequency bands.

Figure 3A shows the relative losses at 40 mc. As in all the graphs, type RG-8/U causes the greatest loss and 7/8" airline the least. The loss is 50 per cent for 250 feet of RG-8/U, which means that only half of the power entering the line reaches the antenna; the other half is dissipated in the line in the form of heat. Where the system requires the delivery of maximum power to the antenna, it may be necessary to use a more efficient line. Even a type RG-17/U, for example, which is more efficient than type 8U, introduces some power loss, reducing the RF power at the antenna. Both the 8/U and 17/U are flexible line with solid dielectric, however, and they are easier to install than airline, which is very rigid.

At 150 mc (fig. 3B) both solid dielectric lines are impractical for long runs. Again, where the use of solid dielectric lines causes greater losses than the system can withstand, it is necessary to use airline.

At 460 mc any appreciable length of 8/U or 17/U line introduces considerable loss, and again airline is recommended. This is particularly important with the 450-470 mc transmitter, where the RF power is limited and every

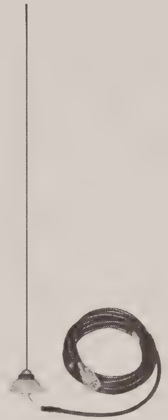
9. See TM11-666, pages 67-69.

bit of it is needed at the antenna. Solid dielectric line is practical for very short distances, as between the mobile transmitter and the roof-mounted antenna; the flexibility of this line is essential for practical installations and the loss will be small where only a few feet of line is required.

Standing Wave Ratio

When the transmission line impedance properly matches the antenna impedance, all the energy reaching the antenna is dissipated in the antenna and none is returned along the transmission lines to the transmitter. This ideal condition is seldom realized in practice, however; there is usually some energy reflected from the antenna, as its impedance varies from time to time with changing conditions. The reflected energy causes standing waves on the transmission line, and this represents a waste of power, resulting in an inefficient system.

The term "standing wave ratio," usually abbreviated VSWR, is the ratio between the maximum and minimum voltages appearing at various points on the transmission line. If the line and antenna impedances are matched (and if there is no reactive component in the antenna impedance), there will be no standing waves on the antenna and the VSWR is 1 to 1. This condition is known as a "flat line." An impedance mismatch of 2 to 1 produces a standing wave ratio of 2 to 1. As this represents a power



A High-Band Roof-Top Whip Antenna. The Transmission Line Connects the Antenna Directly to the Two-Way Radio.

loss of about 11 per cent, almost 90 per cent of the power delivered to the antenna is absorbed by the antenna or radiated into space. This ratio is satisfactory for mobile two-way communications and manufacturers usually specify that any value of VSWR up to 2 to 1 is acceptable for such applications. One of the most practical methods of determining the impedance match and efficiency of the antenna is to use a "thruline" wattmeter. This instrument measures both the outgoing power from the transmitter and the reflected power. The power ratio can be converted to VSWR by means of charts usually included in the instruction manual for these meters. For accurate readings, the meter should be inserted into the line at the antenna terminal rather than at the transmitter end. The readings then represent the power both to and from the antenna. When the meter

is connected at the transmitter end of the line, the readings are altered by these line losses.[10]

Mobile Antennas; the Whip

The grounded quarter-wave antenna is generally regarded as the most practical for mobile vehicles using two-way communications. The body of the vehicle becomes a good ground, particularly for the high-band and 450-mc range. A quarter-wave antenna for the low band would be too long for practical purposes so a loading coil is usually included at the base of the antenna rod to make the antenna electrically longer than its physical length.

A 450 MC Roof-Top Whip Antenna. The Average Antenna Length is About 6 Inches.

These antennas, usually called whips, are about 6 inches long for 450-mc operation. For the high band, they are between 17 and 19 inches long, and for the low band they are between 54 and 96 inches, their exact length depending upon the operating frequency.

The top of a vehicle is usually metal and its area is usually large enough to serve as the ground. Where a top installation is not satisfactory, however, the trunk or some other metal surface of the car may be used, although this usually affects the radiation pattern of the installation. If the vehicle top provides an area equal to or greater than one-quarter wavelength, the radiation will normally be uniform in all horizontal directions (see figure 2).

The greater the distance between the mobile antenna installation and the earth, the more closely will its actual radiation pattern resemble that of figure 2. All objects in the vicinity of the vehicle affect the radiation pattern. The nearer the object, the greater will be its effect on the pattern.

If the whip antenna is fender mounted or lower than the metal roof, the radiation pattern will not be symmetrical horizontally. Instead, the antenna becomes directive, with best reception across the top of the vehicle. In other directions, both transmission and reception will be less satisfactory. For fringe areas, the orientation of the vehicle with respect to the base station may readily be the difference between contact and silence.

10. See TM11-666, pages 74-76.

The polarization of a grounded quarter-wave antenna is vertical.

The radiation resistance of the grounded quarter-wave vertical antenna is theoretically one-half that of the half-wave antenna. For thin wire antennas this is 36 ohms. Thicker wires have even lower radiation resistance. Antennas shorter than one-quarter wavelength usually have a lower radiation resistance; longer antennas have a higher resistance. A 0.3 wavelength antenna has a resistance of approximately 60 ohms.

The proper antenna length is theoretically determined from the standing wave ratio, but from a practical point of view a perfect impedance match is difficult to achieve and maintain. Hence, the antenna is cut for the lowest possible standing wave ratio. When the VSWR is 2 to 1 or less, the system will operate satisfactorily.[11]

Base Station; Isoplane Antennas

The isoplane antenna (fig. 4) is used at base stations. This type of antenna has an equal coverage in all directions and it maintains a VSWR of less than 2 to 1 over the entire band, matching a transmission line having a characteristic impedance of 52 ohms.

There are two sets of ground rods. The upper set is bent downward to increase the impedance. The lower ground rods further improve the horizontal signal, at the same time reducing spurious radiation from the mast or tower.

The isoplane antenna is suitable for both the low band and the high band. It is intended to be used with low and medium power transmitters, not exceeding 250 watts. Any of the transmission lines shown in figure 3 may be used with this antenna.[12]

A Gain Type of Mobile Whip Antenna. Operation is in the 450-MC Band.

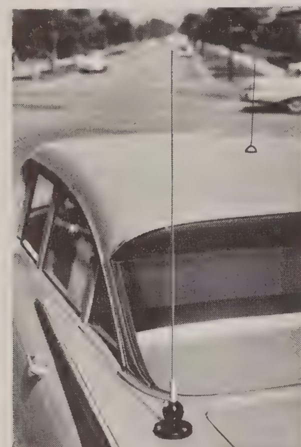
The Unipole Antenna

This base station antenna is one type of ground plane antenna which may be used with both low-band and high-band equipment. As its pattern is omnidirectional (fig. 5B), the unipole antenna is in demand where the base station is located in the approximate center of the service area. As shown in figure 5A, this antenna is folded back upon itself with the unfed end of the antenna grounded. By grounding this end, the antenna affords some freedom from static charge accumulations.

11. See TM11-666, pages 133-134; also "Communications Antennas," reference T-12A.

12. See TM11-666, pages 132-133.

The unipole antenna is one-quarter wavelength long, and four ground rods comprise the ground plane. The impedance is 50 ohms for proper match to the rest of the system.



A Low-Band Fender-Mounted Antenna. The Length of this Antenna Often Makes it Undesirable as a Roof-Top Mount.

Vertical Coax Antennas

Figure 6 shows the evolution of a vertical skirted coaxial antenna from a half-wave dipole. The original half-wave antenna is shown in figure 6A, with the feed lines connected to the two horizontal elements. In figure 6B the elements are rotated to a vertical position, and in 6C the lower element is replaced by a length of tubing--called a "skirt."

Figure 6D shows the final construction. Here the coaxial feed-line is run through the skirt and the inner conductor of the coax is connected to the upper antenna element, producing the upper quarter wave. The outer coax conductor meanwhile is connected to the skirt. Thus the arrangement is a half-wave antenna, vertically polarized.

Skirted coaxial antennas are used at base stations and they are designed for both 24-54 mc and 144-174 mc. For the low-frequency band, one skirt is used, as shown to the right of figure 7. These antennas are extremely rugged. They are sealed against humidity, and changes in weather have little or no effect on them. They have a power rating of 1,000 watts and a VSWR of less than 2 to 1.

When carefully designed, the skirted coax antenna will present the proper matching impedance of 50 ohms. The antenna is omni-directional, having a radiation pattern which is consistently uniform in the horizontal plane.

Additional skirts below the antenna proper become practical on the 144-174 mc band. They are used to prevent radiations from spurious induced voltages in the tower or feed line. Two additional parasitic skirts are shown to the left of figure 7, and the central figure shows the complete skirted coaxial antenna at the top of a tower.

Omnidirectional "Gain" Antennas

Neither the unipole nor the isoplane antenna provides any gain in field strength, and the skirted coaxial antenna offers no gain over a standard dipole, but they all serve well as omnidirectional base station antennas.

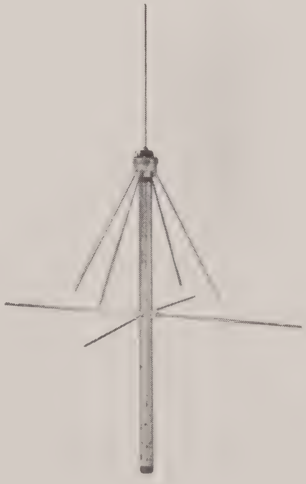
If some gain can be realized in the antenna, it is just as good as if the transmitter power output were increased. For example, if an antenna has a gain of 3 db in actual operation this is the same as if the transmitter power were doubled, for 3 db represents a power ratio of 2 to 1.

Of course this antenna gain does not mean that the antenna actually sends out twice as much power-- no antenna can radiate more power than it receives. The antenna radiation pattern is changed, however, so that the radiated energy is concentrated in some direction. The omnidirectional gain antenna "squeezes" the radio wave into a narrow horizontal beam extending parallel to the earth.

Figure 8 shows the pattern of an antenna having a 6-db gain in all horizontal directions. The height of the beam is only about 10 degrees but for two-way communications there is no need to transmit power at higher angles, since this power is unused and therefore wasted as far as the system is concerned.

Omnidirectional gain antennas usually operate as a colinear array, which means that several dipole antennas are stacked on top of each other and properly phased to provide the desired radiation pattern. These antennas are practical for the 450-mc band, as well as for the high band.

The gains of two-way communications type antennas are usually given in comparison with the radiation of a half-wave dipole antenna. The gains of parabolic and other microwave antennas, however, are usually given with respect to an isotropic antenna, a theoretical point source which radiates equally well in all directions. If we compare the half-wave dipole to the isotropic antenna, the dipole has a 2.2-db gain.



An Isoplane Base Station Antenna. This Particular Antenna is Cut for the High Band.

Directional Antennas

There are various applications for directional antennas in two-way communications. The antenna might be located at one end (or in a corner) of the service area, or the station might be used for repeater purposes and desire contact with only one fixed location. Bidirectional antennas are particularly suitable in railroad installations where the coverage is confined to a narrow path along the right-of-way.

The remaining antennas to be discussed in this lesson are directional. They all sacrifice the omnidirection pattern so that more of the RF energy can be concentrated in some horizontal direction.

A 450-MC Gain Type Antenna Having Omnidirectional Characteristics.

The Cardioid Antenna

This antenna can be used on both low and high bands, and it is designed for base stations, where it is located at one end of the service area. The cardioid antenna (fig. 9A) is a modification of the unipole antenna in which a parasitic element acts as a reflector. There is very little radiation from the antenna in the direction of the added element, but in the forward direction the gain is approximately 3 db, a power ratio of 2 to 1. The horizontal radiation pattern is shown in figure 9B. The front-to-back ratio of the antenna is about 15 db, a power ratio of about 30 to 1.

By concentrating the energy within the service area instead of radiating it in all directions, much unnecessary interference is eliminated. When used with the receiver, the cardioid antenna is very effective in rejecting interfering signals from unwanted directions.

Bidirectional Antennas

This antenna is suitable for serving long thin geographical areas such as railroads, pipelines or highways. It consists of two ground-plane antennas spaced one-half wavelength apart, both antennas being fed from the transmission line (fig. 10A). The radiation pattern is shown in figure 10B. The gain along the direction of the antenna is 3 db, a power

increase of 2 to 1. The bidirectional antenna is applicable to both high and low bands.

The Corner Reflector Antenna

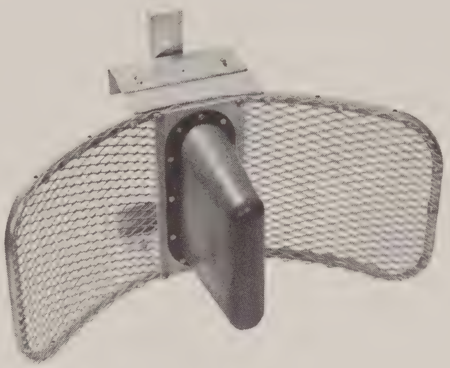
Figure 11 shows a high-gain unidirectional antenna for the 144-174 mc range. The radiation pattern is also shown in figure 11. The corner reflector is used with base stations--repeater stations in particular--for maximum contact in one direction only. When receiving signals from one direction, there is some rejection of noise and interfering signals from other directions. The gain of the antenna is approximately 7.5 db, a power ratio of 5.6 to 1.

The Helix Antenna

The helix is another high-gain unidirectional antenna. This antenna consists of a coil of wire encased in a hard resinous insulating material. The helix antenna is fed at one end and operates in conjunction with a ground plane. With the diameter of the coil equal to about one-third of a wavelength, the radiation pattern is very narrow. The beam is radiated directly from the end of the coil, resembling light rays from a sharply focused light source such as a flashlight. The relationship of wavelength to coil diameter restricts the use of this antenna to the 450-470 mc band.

When the circumference is approximately one wavelength, the field is circularly polarized and the direction of polarization may be either to the right or to the left, depending upon the manner in which the coil is wound. For a right "sense" at the transmitter, the receiving antenna must also have a right-turn antenna. If the receiving antenna is oppositely sensed there will be no system gain, for the receiver antenna tends to reject the incoming signal. This makes it possible to reject unwanted signals produced by other helix antennas in the same area. If the interference has a right spin the system can use a left spin with some improvement in interference rejection.

The gain of the helix can be as high as 12 db, and this may be even greater by increasing the number of turns. The angle of the transmitted wave may be as low as 12 degrees, however, requiring careful orientation of both antennas for maximum pickup.



A Highly Directional Antenna Used for "Point-To-Point" Communications. Operation is in the 960-MC Band.

This Specialized High-Band Antenna is Used Extensively in Railroad Radio Applications.

The Parabolic "Dish" Antenna

These antennas are used almost exclusively in microwave, with certain unique applications having been found for them in the 450 and 960 mc bands. The size of the dish antenna at 450 mc makes it rather expensive; wind resistance and other physical problems are also often troublesome. High gains can be realized, however, if the dish is sufficiently large. There is some possibility that such antennas will be used more extensively in both the 450 and 900 mc range, and the serviceman should be acquainted with their characteristics and operation.

This antenna beams the energy in a very narrow angle, thus realizing a very high gain. At 900 mc a 15-foot dish has a gain of 30 db, which represents a power ratio of 1000 to 1. The same dish at 450 mc has a gain of about 24 db, a power ratio of 250 to 1. A 10-foot dish at 450 mc has a 21 db gain (125 to 1) and on 900 mc it has a ratio of 500 to 1. Smaller dishes (of about 6 feet) have proportionately smaller gains, but their gain is still higher than can be obtained from other antennas at the same frequency.

The sharp orientation of the parabolic dish antenna makes it applicable only for point-to-point contact. Its high gain and excellent rejection of interfering signals recommends its use wherever the installation is at all practical.

The Service Area

The Communications Systems Engineer, if given (1) a specific amount of base station power, (2) the frequency of operation, (3) the type of antennas, and (4) antenna heights, will readily predict the distance that a system will cover with good reliability. Hardly stopping to take a breath, however, he will add that these figures apply only where the terrain and other conditions for propagation are normal. Thus, while the probable coverage can be projected, the true coverage can be determined only from a comprehensive survey.

A fairly accurate idea of the coverage that may be expected can usually be obtained by comparing the proposed installation with a similar one which is already in-

stalled and operating. Because no two systems can be exactly alike, however, this method is not always valid.

Another procedure is to set up a trial system which closely simulates the proposed system, and then accumulate test data. The closer the trial system comes to duplicating the final system, and the more tests that are made, the more accurate will be the prediction.

Local conditions control the maximum coverage of any system. In determining the probable coverage, engineers must take into consideration the topography, manmade and natural obstacles, foliage, transmitter power and receiver sensitivity, antenna heights and gain, channel frequency, transmission line losses, noise level, interfering signals and space attenuation.[13]

Antenna Receiving Characteristics

As an "interceptor" of electromagnetic energy, the antenna exhibits the same characteristics when used for receiving as it does when used for transmitting. Thus the receiving antenna must have certain standards of gain, directivity, and so forth, as well as the transmitting antenna. While there are many instances in two-way communications where different antennas are used for receiving and transmitting, the same antenna serves both functions in most installations.

The antenna impedance must be closely matched to the rest of the system during transmission periods, for any appreciable mismatch here can reduce the amount of power that is actually radiated into space. A mismatch which would be objectionable when transmitting may not cause any great change in reception. In fact, a mismatch is often actually introduced at the receiver input in order to improve the noise figure. In most installations, the impedance of the antenna system is standardized at 50 ohms. This is the impedance of the antenna. It is also the impedance of the receiver input, the transmitter output, and the transmission lines. For fixed frequency operation--usually the case with mobile applications--an impedance of 50 ohms can be maintained within a reasonable value. Where the system must operate over a relatively wide band of frequencies, however, constant impedance may become more of a problem.

Where poor results are obtained at the outer edges of the service area, a high-gain antenna at the fixed or base station may solve the problem. The gain of the base station antenna is of importance both in transmitting to the mobile units and in receiving from them. When a sacrifice in gain does not disrupt coverage in other areas, a directive array may be used. By favoring one particular area, such an array will often provide the desired coverage.

13. See "Obtaining Optimum Performance In a Mobile Communications System," reference T-12B.

STUDENT NOTES

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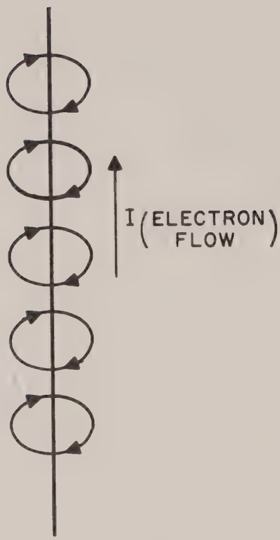
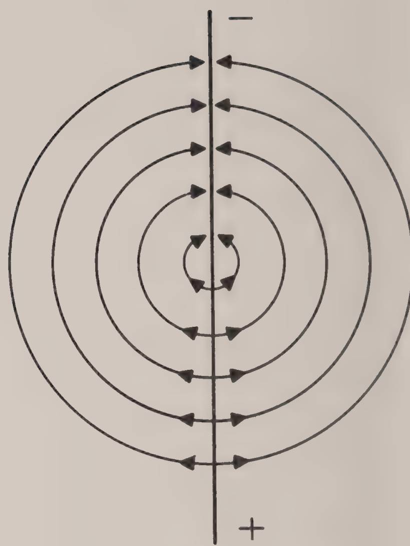


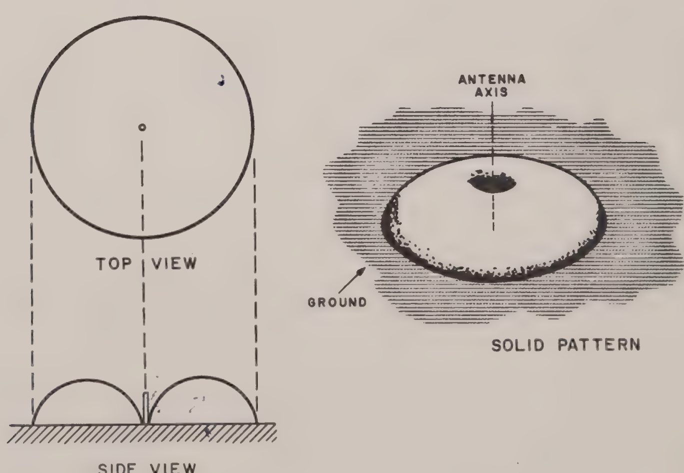
MAGNETIC FIELD
ABOUT THE ANTENNA

FIGURE 1A



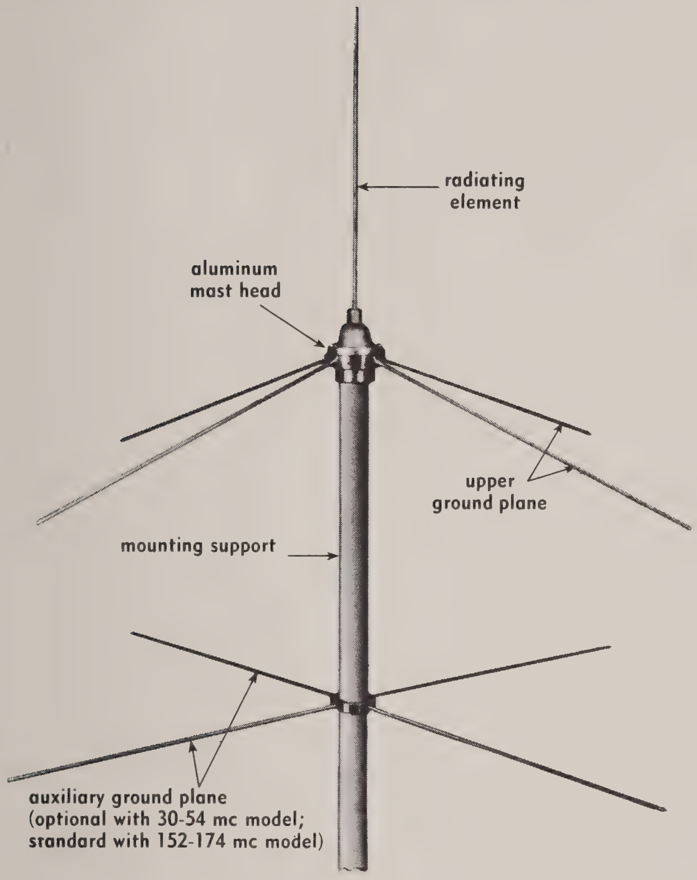
ELECTRIC FIELD
ABOUT THE ANTENNA

FIGURE 1B



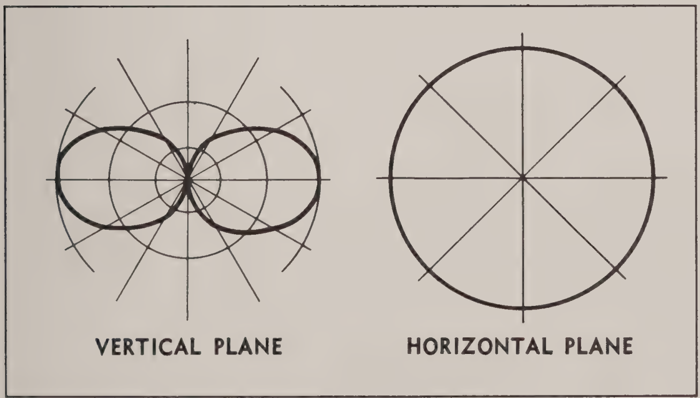
RADIATION PATTERN PRODUCED BY A GROUNDED QUARTER-WAVE ANTENNA

FIGURE 2



ISOPLANE ANTENNA

FIGURE 4A



RADIATION PATTERN

FIGURE 4B

STUDENT NOTES

STUDENT NOTES

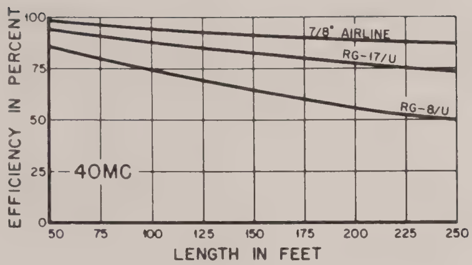


FIGURE 3A

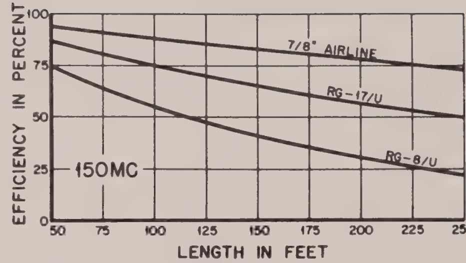


FIGURE 3B

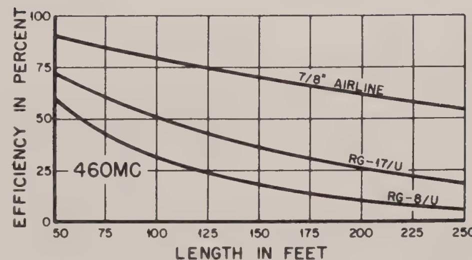
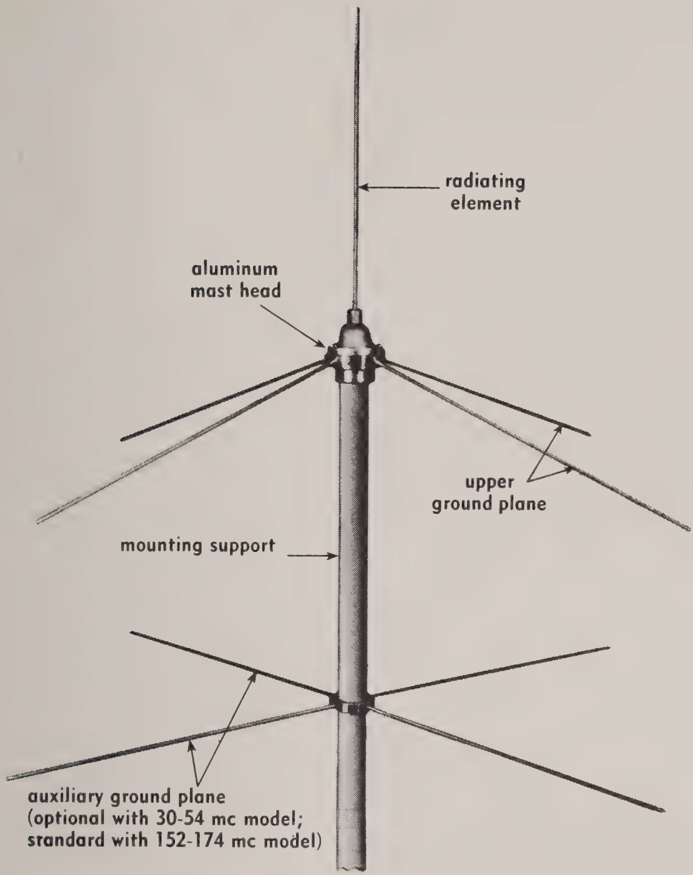


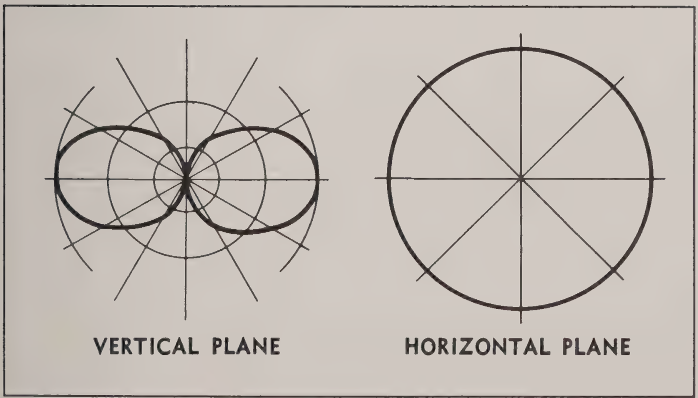
FIGURE 3C

TRANSMISSION LINE EFFICIENCY CHARTS



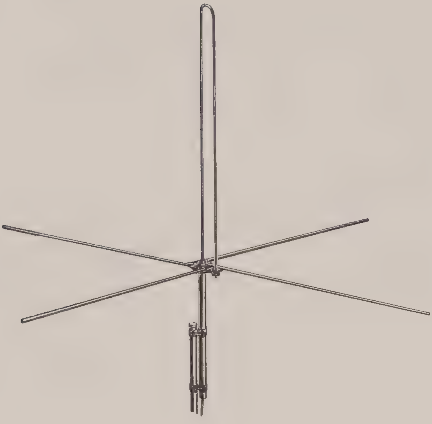
ISOPLANE
ANTENNA

FIGURE 4A



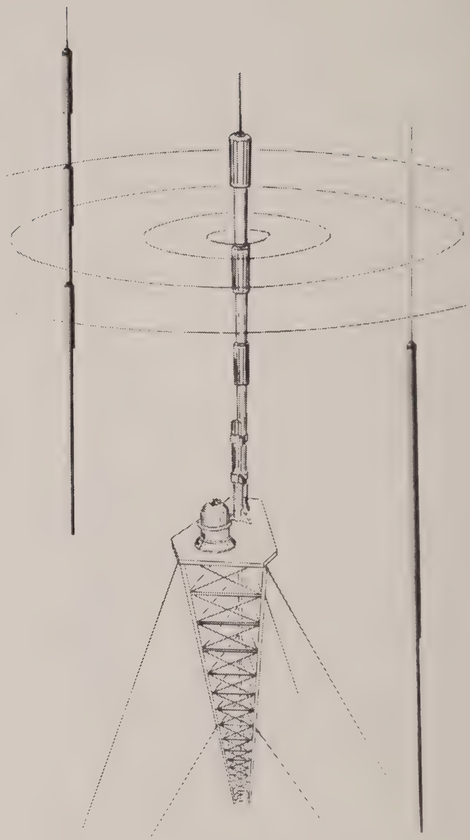
RADIATION
PATTERN

FIGURE 4B

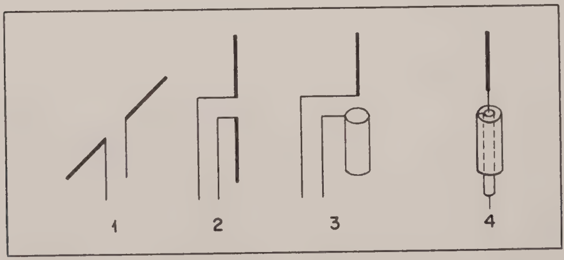


UNIPOLE ANTENNA
FIGURE 5A

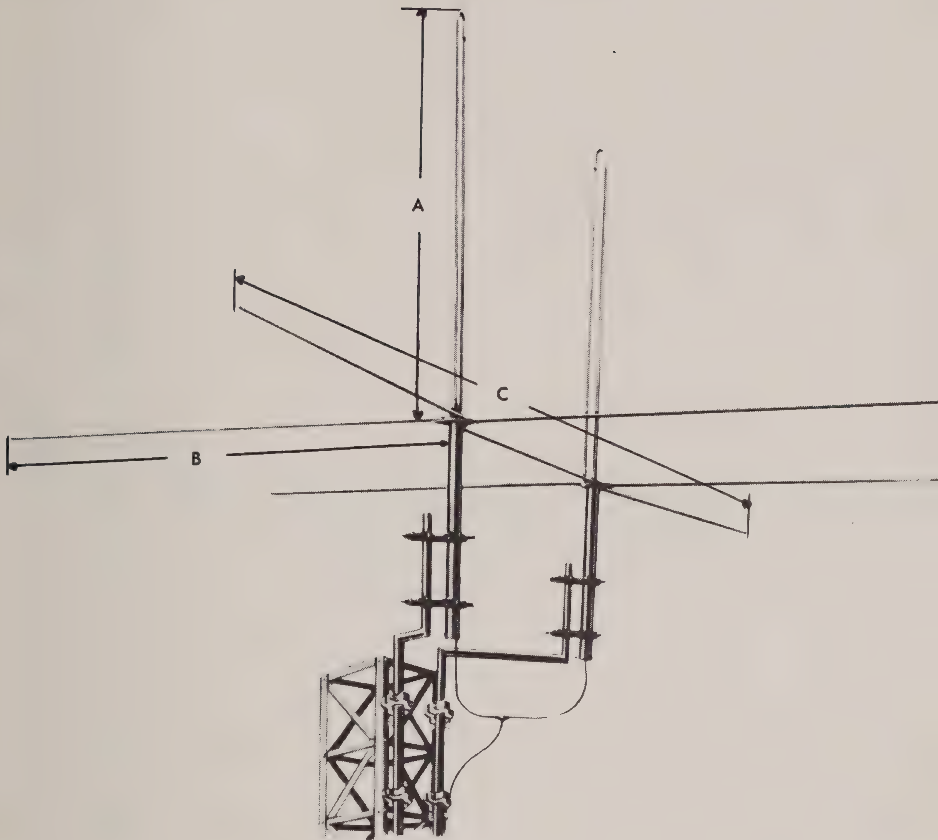
HORIZONTAL PLANE
FIGURE 5B



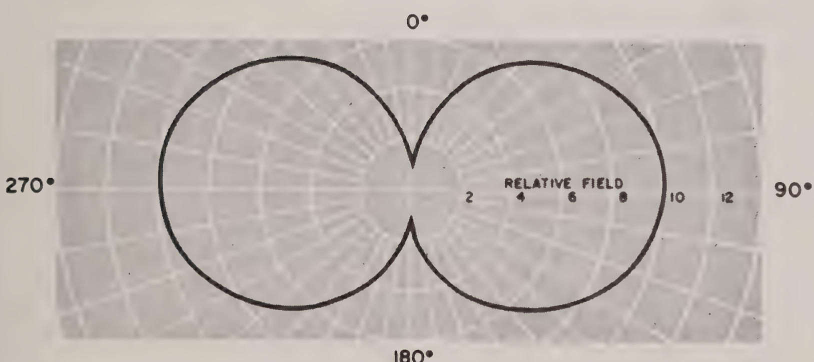
SKIRTED COAXIAL ANTENNA
FIGURE 7



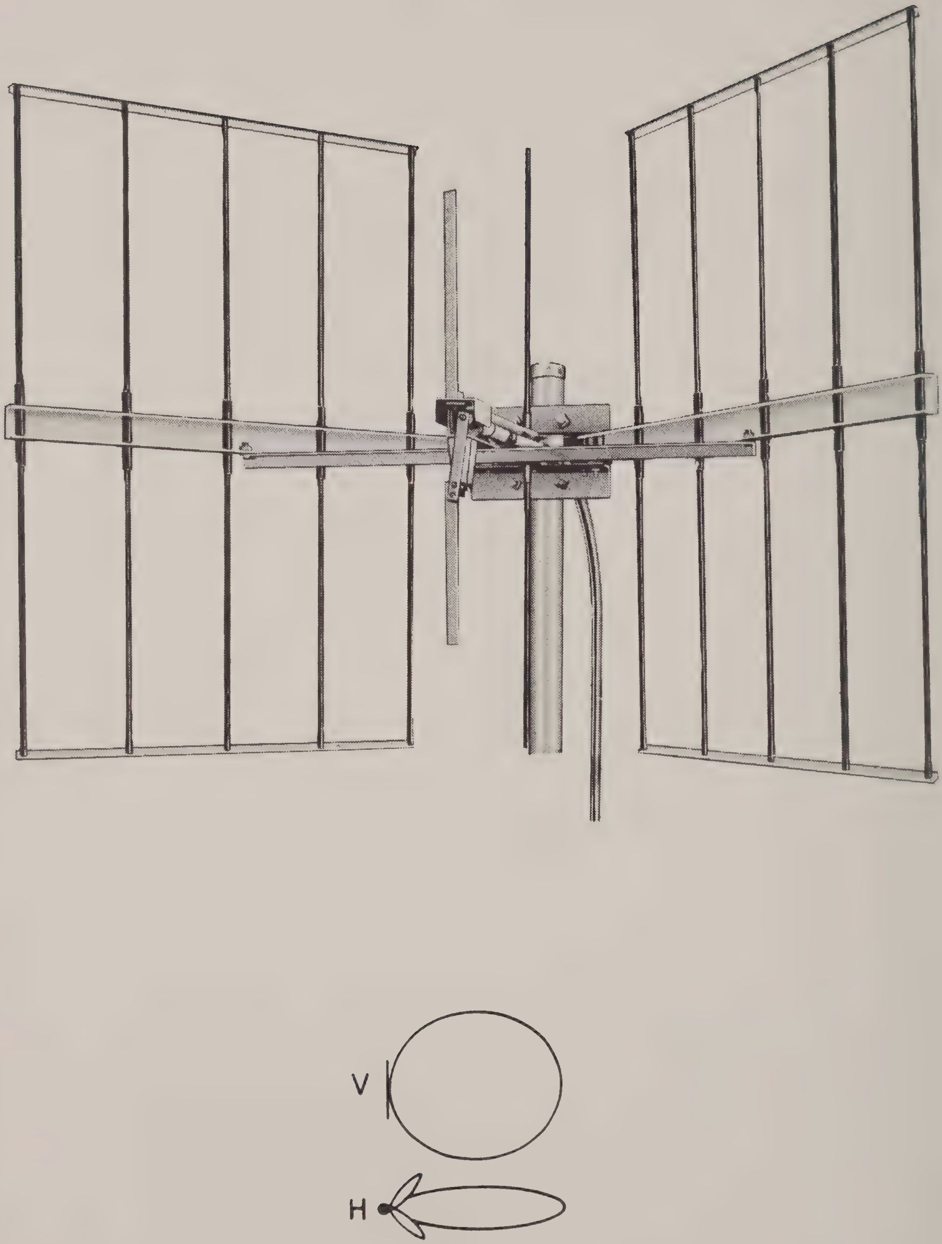
EVOLUTION OF THE COAXIAL ANTENNA
FIGURE 6



BI DIRECTIONAL ANTENNA
FIGURE 10A



HORIZONTAL RADIATION PATTERN
FIGURE 10B



CORNER REFLECTOR ANTENNA

FIGURE 11

national

MOTOROLA

RADIO COMMUNICATIONS

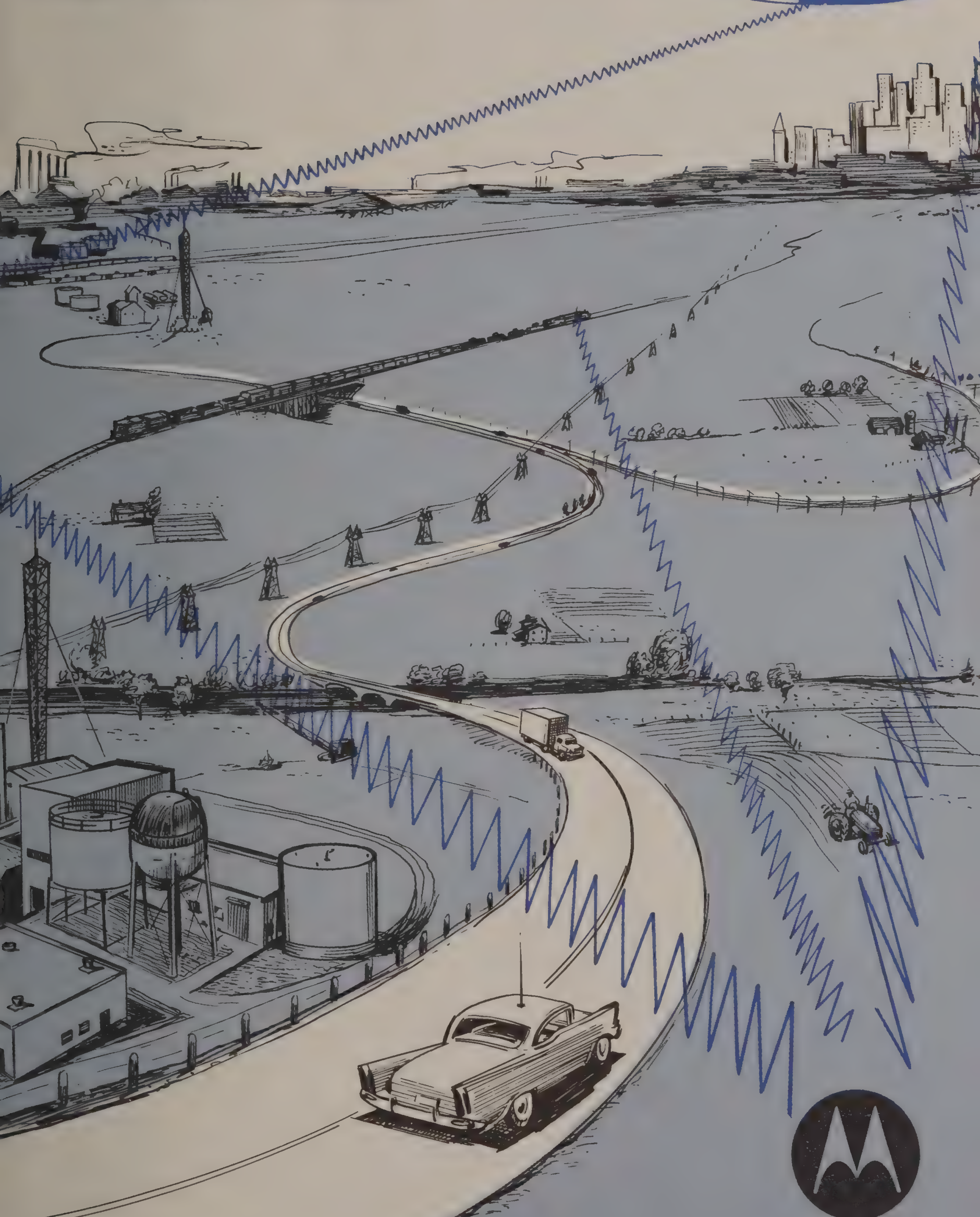
service

INTRODUCTION TO THE *MOTOROLA*

TWO-WAY FM RADIO

HOME STUDY COURSE

national MOTOROLA RADIO COMMUNICATIONS service



MOTOROLA

TRAINING INSTITUTE

4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS

Introduction and Index

to the Motorola Two-Way Radio Communications Training Program

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This booklet is an Introduction and the Index to the complete Motorola Home Study Course, which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The course covers mobile, portable, and base station equipment, including the latest transistorized units.

INTRODUCTION AND INDEX

Contents

national

MOTOROLA
RADIO COMMUNICATIONS

service

INTRODUCTION and INDEX

Let's Get Acquainted

We wish it were possible to greet you personally and sit down and talk over your training program. We would also like to introduce you to the people responsible for Motorola Training Institute so that you would feel right at home with us. Since it is not possible to do this, we have to tell you all about your training via this booklet.

First, Motorola Training Institute is not a large correspondence school. It has been established for one basic purpose: to train men to become competent technicians in the rapidly expanding field of two-way mobile radio. Mr. Dan Noble, President of MTI and Vice President of Motorola, Inc., has long believed that there should be a specialized training to help men to become more competent technicians. This ambition has at last been realized.

Motorola Training Institute has come into existence directly as a result of Mr. Noble's direction and supervision. Thus, MTI is not destined to become a school in which the student is just a "number." Instead, it is our purpose to personally supervise your training, lesson by lesson, so that we will know you are making progress in understanding two-way radio and its service techniques.

In this Introduction-Index booklet we will explain the training program. We want to be certain that you know what is expected of you in order to successfully complete the training. We have also included some comments about the method of study, methods which have proven to be successful, and, at the very end of this booklet, you will find a subject-matter Index with references to the various lessons.

WELCOME to Motorola Training Institute.

The Training Material

The training material consists of (1) 38 lessons, (2) a number of text books used as required reading material throughout the training, and (3) many reprints of vital technical articles published in a variety of technical trade magazines, etc.

Your Course Material is Complete, Including LESSONS, REFERENCE TEXT BOOKS, and REPRINT ARTICLES.

The Lessons

There are 38 lessons in the complete training, each devoted to some phase of the operation or servicing of the two-way radio system. These lessons have been carefully planned and written under the supervision of Motorola engineers and field service personnel. It is thus assured that the lessons are not only technically correct, but they also contain the information which you, the service technician, should know if you are to be successful in your endeavors.

The lessons are printed as small, pocket-size booklets. This makes them easy to read and handy to carry in your pocket. The diagrams for each lesson are at the back of each lesson, on foldout pages. This enables the reader to have each diagram before him at all times while he is studying the text; he does not have to turn from one page to another to look at a figure or diagram.

There are also many photos and illustrations throughout each lesson, to illustrate the equipment and principles being discussed.

The Text Reference Books

A number of text books are included with the course as part of the training, at no additional cost. These texts are considered as an integral part of the training and are sent along with the first mailing of lessons. Specific page references are made to these various text books in the lessons. This additional study material enhances the lesson explanations.

The text books are of two types. First, some are concerned with fundamentals and contain explanations about basic principles. Although we assume that the student knows most of these things, we realize that it may have been some time since he has studied these fundamentals and may be a little "rusty" on some. A quick review will be helpful. These text books cover such basic relationships as DC and AC principles and fundamentals of vacuum tube and transistor operation.

The remaining text books give additional discussions and data on the subject being discussed. Such texts deal with FM Reception and Transmission, Antennas and Wave Propagation, Pulse Techniques, Transistor Applications, and Test Equipment. These references give the student an opportunity to delve further into many of the subjects which are discussed in the lessons, but which, because of their nature, are not developed to their fullest.

Thus, even the advanced student can go about as deeply as he wishes in this course. The texts will serve as good reference books for future use. Few men would take the trouble to collect the valuable texts included with the course.

"Reprint" References

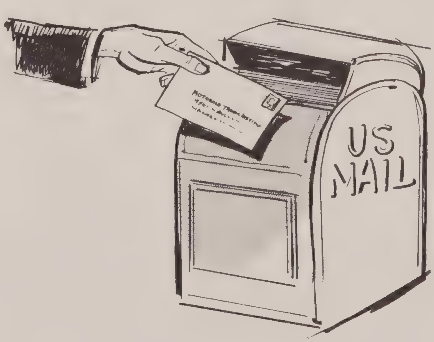
Many articles, which have appeared in magazines and other publications, are of prime interest to the student. Many of these articles have been reprinted and are sent along with the lessons as additional study material. These articles are also referred to in footnotes in the lessons, so that the student will know exactly when to study them.

There are several reasons why these text books and articles have been included as a direct part of the course. First, some of the reading material is necessary to help the student "brush up" on the fundamentals which are not too well understood. Second, additional explanations and examples add to the total understanding of the material being discussed.

Rather than merely make reference to these additional readings and leave the responsibility of securing them to the student, they have been included to make sure that they are in the hands of the student when he needs them and therefore are likely to be studied. Furthermore, some of the references are not readily available to the average student; others have appeared in publications which are unlikely to be in any public library or book store.

Home-Study Has Real Possibilities

In addition to the direct benefit which you will receive from this training, there are many intangible advantages to a home-study training of which you may not be aware. First, you are able to establish your own study schedule to fit in with your other activities and



Mail Your Exams Promptly to Assure a Constant Supply of Advanced Lessons.

work schedule. Thus, you are not required to attend a class at certain hours, and you will not be penalized should you find it necessary to temporarily discontinue your studies for a few days or more; you can make it up later, when you have a little more time. Thus, by means of a home-study program you are allowed to set your own progress rate and are not encumbered with a schedule which you must meet. But do not procrastinate--don't put it off.

Furthermore, we all know that individuals progress at different speeds. Home-study methods automatically take care of this difference; you are not required to keep pace with a class when you want to take a little extra time to review some principle which was never too clear to you, and you are not held back by a class when you encounter something which you already know.

Another great advantage of home-study training is that you learn to make your own decisions. You become more self reliant. There is nobody at your side to prod you along when you have some doubt, and you learn to dig out the facts for yourself. Knowledge gained in this fashion is more fully understood, and is longer remembered. Also, if you become momentarily "stuck" on something, all is not lost. All you have to do is send us a report of your problem, making the nature of the doubt as clear as possible, and we will be glad to give you the help you need. Many times you automatically answer your own doubts by the time you receive our answer, for the mere fact that you have clearly defined your problem and think about it for a few days allows you to deduce the answer for yourself. Thus, in many instances you will find that our answer merely confirms what you have already decided. This gives real understanding and confidence.

Success is Near, with Good Study Conditions.

Home-study methods also enables the student to determine when he wishes to study. The person who has time to study early in the morning and finds that this is the very best time for him to get things done, will hardly find any class or other means of learning at this time of the day except by a home-study course. Or, regular school sessions or night classes are often in conflict with your work program and other commitments, so that you find it impossible to take full advantage of them. The home-study method is again the logical solution.

How To Study

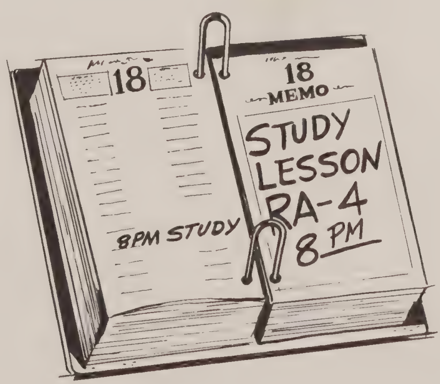
The successful completion of this training course requires a certain amount of endeavor on the part of the student. The exact number of hours required will vary just as much as the abilities, backgrounds, and ambitions of the students taking the course. We can suggest some basic ideas to help each student get the very most from this program.

The first and perhaps the most important factor in successfully completing the course is to establish a routine study habit from which there is no departure. It is of prime importance to designate a certain part of each day or week as study time, and then to observe this schedule without interruption. There are many factors which determine the best study time for any one person, so the answer to this problem is determined individually. It makes little difference what time is chosen so long as we exclude all outside factors and devote this time solely to study.

The fact that you have undertaken this training proves your ambition. It is now up to you to realize fully the advantages offered to you by excluding as many distracting influences as possible. There will be no one except yourself who will be responsible for your progress so it will be up to you to be the director of your efforts. This is excellent training and self-discipline and it is certainly a great accomplishment to take on a program of this kind and see it through to the finish.

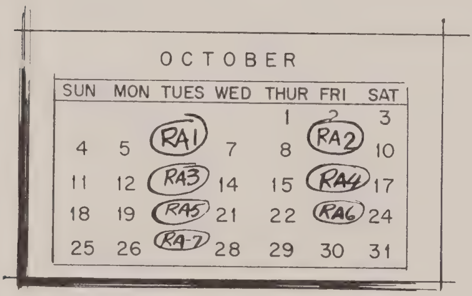
In choosing a place to study, it is essential to have some place all to yourself without any distractions of radios, TV sets, youngsters, etc. Also, it is better to have a regular desk and chair for your study periods, for the easy chair tends to make a person relax, specially after a full day's work, to the point that we also relax mentally and do not fully utilize the time spent. Nothing should interfere with your study period. By enforcing a strict program on yourself, your friends and family will soon come to respect your wishes in this matter.

The lessons have been planned so that each should be studied in the designated sequence and "one at a time." The explanations of each lesson depends upon an understanding of preceding lessons if



Make PROGRESS a Daily Habit.

you are to achieve full understanding of the purpose and importance of the circuits and their method of operation. In order that the lessons will be studied in their intended order, each series of lessons is numbered. Thus, you will start with lesson 1 of a certain series. Your first lessons, about receivers, are coded with the letters "RA", and you should study lesson RA-1 first, lesson RA-2 second, etc. After the receiver lessons are completed, you will start on a new series of lessons, and these have different coding letters.



Plan Your Work—Work Your Plan.

When you receive your first shipment of lessons and the reference books, we want you to thumb through each of them, to become acquainted with each. After you know what is in the various lessons and texts, you are now ready to start on lesson RA-1, "What is Frequency Modulation?"

The first time through a lesson you should read it almost as you would a novel. Do not stop any great length of time to ponder on something which you do not understand; the purpose of this first reading is only to get the overall idea of the lesson, and to find out what you are expected to learn. In reading the lesson the first time, do not be concerned with the footnotes except to know that they are there. Do not attempt to read the additional references in the text books.

After you have gone through the lesson once or even twice in this manner, you are then ready to make a more detailed analysis. Now you should stop and think over any portion that is not fully clear to you. The lesson should not be read as a novel during this study; instead, it should be analyzed paragraph by paragraph. If there are some sections which are not entirely clear, it is likely that there is a reference to one or more of the text books and reprint articles, and now is the time to make use of this additional study material. The specific books and pages are given. Even though you are satisfied that you understand what is being said, when you come across each of the references, it is recommended that you stop and read this other material. It will add to your overall understanding of the principles and equipment. The better you understand something the better prepared you are to determine what is wrong when trouble develops. This is the ultimate goal of this training.

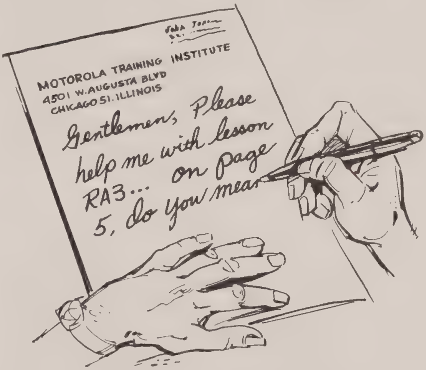
If, after studying the lesson and the references a reasonable number of times, you have some doubts

or questions about the material, you may follow any of several procedures. First, you may realize that perhaps your questions are merely anticipating some explanations which will be given in the future.

For example, you read about a discriminator in lesson one, and realize that there are some things about the discriminator you do not yet understand. In fact, after reading the second lesson where the discriminator is again mentioned, there may still be something which you do not understand. A quick look at the lesson schedule discloses that a future lesson is devoted entirely to the discriminator.

Thus, we gather that we are not expected to know all about the discriminator in those early lessons; we are merely expected to achieve an overall view of the discriminator's purpose and general function; detailed explanations of the operation are given later. If this is your problem, the obvious conclusion is that you are anticipating what is coming in future lessons and you should wait until you study the latter lesson. Just look ahead and assure yourself.

There may be a question about the overall purpose and operation of the discriminator, however, which should be answered for you at this time. Again there are several things which you may do, depending upon your interpretation of what is best. You may decide that the missing information or doubt will not stop you from going ahead with your studies in a normal manner, and you may do just that. At the same time, however, send in an inquiry, either separately or with the examination. When we receive your specific question we can give you a direct reply and satisfy your doubts.



Assistance is Always as Near as Your Mailbox.

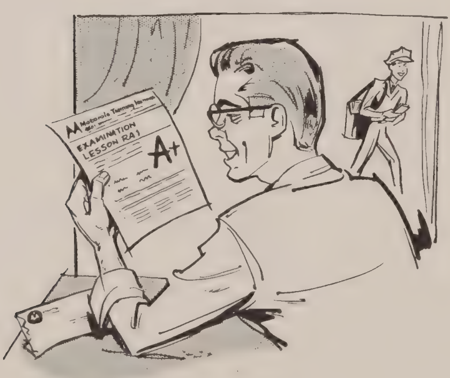
On the other hand, if you feel that the information is essential to the study of the lesson, you can lay the lesson aside and rush an inquiry to us, giving complete details and specific questions for us to answer. In the meantime, you should at least start reading the next assignment.

Plan Your Study Program

You can get as much out of a good home-study course as you are willing to put into it! So, apply yourself. Establish a planned study program. Plan your work--and work your plan!

The Examinations

At the end of each assignment there is an examination on a fold-out sheet. These examinations are the only means we have of determining your progress through the training. Thus, we urge you to be very careful in completing them and prompt in sending them to us for grading. The questions are all of the objective type and require very little writing on your part. The type of question is varied, to accommodate measurement of your understanding of the lessons and to lend greater interest to the examinations.



Your Graded Exams—with Helpful Comments—are Returned Promptly.

After you have completed the study of a lesson to your satisfaction, it is time to look at the examination for the first time. It is advisable not to look at the examination during the study of the lesson, for this too easily leads to "answer looking" rather than an intelligent digestion of the lesson material. Answering the questions successfully is not the most important thing of your training; understanding the material is.

In reading the examination questions, do not attempt to answer any of them the first time through. Instead, read the questions intelligently in order to determine what is required in each. After this is done, the questions can be tackled one at a time; answer all of the questions of which you are sure without making a review of the lesson. It is then time to go back and review the lesson explanations with respect to any of the questions.

We expect you to make full use of the lessons explanations in completing the exams. It is not considered as "cheating" if you review the lesson. A comparison can be made here to a service problem. Surely you are expected to make full use of schematic diagrams and other service information in repairing electronic equipment; nobody is required to memorize all this information. Instead, the service technician makes intelligent use of all the information he has access to, thereby giving the best and most reliable service to the customer. The same applies to the lesson exams. The greatest percentage of our knowledge is that which we know how to find rather than what we have memorized.

Grading System

Our method of grading is relatively simple. Questions are marked as right by a check (✓) and wrong by a question mark (?). Some questions may receive partial credit, in which case the amount deducted from full credit is indicated, for example, -2, -5, etc. The final grade for any examination is by an alphabetical system, as follows:

Assigned Grade	Numerical Equivalent
A+	97-100
A	93-96
A-	90-92
B+	87-89
B	83-86
B-	80-82
C+	77-79
C	73-76
C-	70-72
"Correct and Return"	below 70%

As indicated, the lowest passing mark is 70%, or C-. Papers below this level are not acceptable; they receive no final mark, but are stamped "Please Correct and Return" and require further consideration on your part. When this paper is returned to you, instead of the regular answer sheet sent with examinations, a "Help Sheet" will be substituted. This

.... a Big Job Well Done.

will guide you with those answers which were wrong. (These help-sheets are available to you for any examinations which may give you trouble.) Examinations which are returned to you "Correct and Return" must be sent in for grading a second time. There is no sacrifice in the final grade because of the second attempt; the examination may still earn a perfect grade. Only one revision is allowed, however, so it is important that you reconsider each wrong question very carefully and make sure that the revised answer is correct.

Failure in one or a few examinations is not an indication that the student is failing the course, but these should be avoided if at all possible. Where you are having trouble with examinations, it may be well to write and tell us your problems. Perhaps we can give you the help you need to go ahead successfully.

At the end of your training an average will be taken of the individual lesson grades, and this average will count considerably in determining your final grade.

Final Examination

A final comprehensive examination is given at the end of the training. This is about the only way in which we can be sure that you have achieved what is expected of you in the course. The examination is sent to you along with the last series of lessons, and this enables you to start on the final as you complete the last lessons. The only specific time limit during which this exam must be finished is that it must be completed and submitted not later than 18 months after enrollment. We urge you to complete it without delay. Because this final is a challenge to you and what you have attained from the training, consultation service of a specific nature is withheld. A review of the individual lessons and their examinations, however, will normally give you the assistance you need to analyze any question and determine the correct solution.

The final examination papers are not returned to you except that they may be failing the first time and require reconsideration. Otherwise the finals are retained in our files.

The final examination also counts appreciably in your final grade, and certificates are issued for a final passing average of 70%. Failure in either the individual lessons or the final examination thus does not prohibit "graduation" as long as the final average is 70% or above.

Not the End....
Just the BEGINNING.

Certificate of Graduation

When you have successfully completed the training, including the final examination as well as the examinations of the lessons, you will receive a CERTIFICATE stating your accomplishment. You will be proud of this CERTIFICATE, for it certifies that you have prepared yourself well to service two-way radios--you have the "know-how," the understanding and background, to be a success in your chosen field.

The CERTIFICATE is very suitable for framing and may be placed in a prominent place in your office or shop. It will be there for everyone to see. They will recognize that you are the person to keep their two-way radio systems in constant peak performance.

SUBJECT INDEX

To Motorola Home-Study Lessons

SUBJECT AND LESSON

national

MOTOROLA
RADIO COMMUNICATIONS

service

national

MOTOROLA

RADIO COMMUNICATIONS

service

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON INDEX

Lesson Index

MOTOROLA TRAINING INSTITUTE

Here's what the MOTOROLA TRAINING

38 LESSONS

RECEIVERS

What is frequency modulation?
FM communications receiver—block diagram analysis.
The RF amplifier.
The high frequency oscillator—mixer and first IF amplifier.
The second mixer, oscillator and IF stages.
The limiter.
The discriminator.
Squelch and audio circuits.
The meter in the communications receiver.
Receiver specifications.

TRANSMITTERS—POWER SUPPLIES—ANTENNAS

FM transmitter block diagram analysis.
Transmitter oscillator.
The phase modulator.
The audio circuit; deviation control.
Frequency multiplication.
Power amplifier.
The meter in the transmitter.
Transmitter specifications.
Power supplies—general.
Vibrator and dynamotor supplies.
Transistor switch and AC power supplies.
Antennas and transmission lines.

SERVICING AND SPECIAL EQUIPMENT

"Private-Line" systems.
Selective signaling equipment.
Test sets.
General trouble shooting.
Receiver servicing.
Transmitter servicing.
Test equipment.
Installations and preventive maintenance.

TRANSISTORS

Semiconductor materials.
Germanium and silicon diodes.
The transistor.
Transistor amplifiers.
Transistor bias—DC stability.
Transistorized audio equipment.
Transistorized receiver circuits.
Servicing transistorized equipment.

ISTITUTE *course in* 2-way radio *includes:*

9 REFERENCE TEXT BOOKS

In addition to the 38 lessons, you will be supplied with reference texts—included with the training at no extra cost—to be used as supplementary reading and study material. The text books will be changed periodically so as to continually keep you supplied with the most up-to-date and suitable texts available.

Basic theory and application of transistors.
FM Transmission and Reception.
FM Transmitters and Receivers.
Pulse Techniques.
Antennas and Wave Propagation.
Handbook of Test Methods and Practices.
Electrical Fundamentals (DC)
Electrical Fundamentals (AC)
Theory and Application of Vacuum Tubes.

MORE THAN 20 ARTICLES

Also supplied are pertinent reprint technical papers and articles dealing with two-way radio systems, equipment, operation and maintenance.

HERE ARE A FEW TITLES:

Utilizing the new split-channel frequencies.
Communications antennas.
Suppression of ignition noise in mobile equipment.
System maintenance of two-way radio.
On locating intermittants.
Frequency modulation.
The split-channel story.

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